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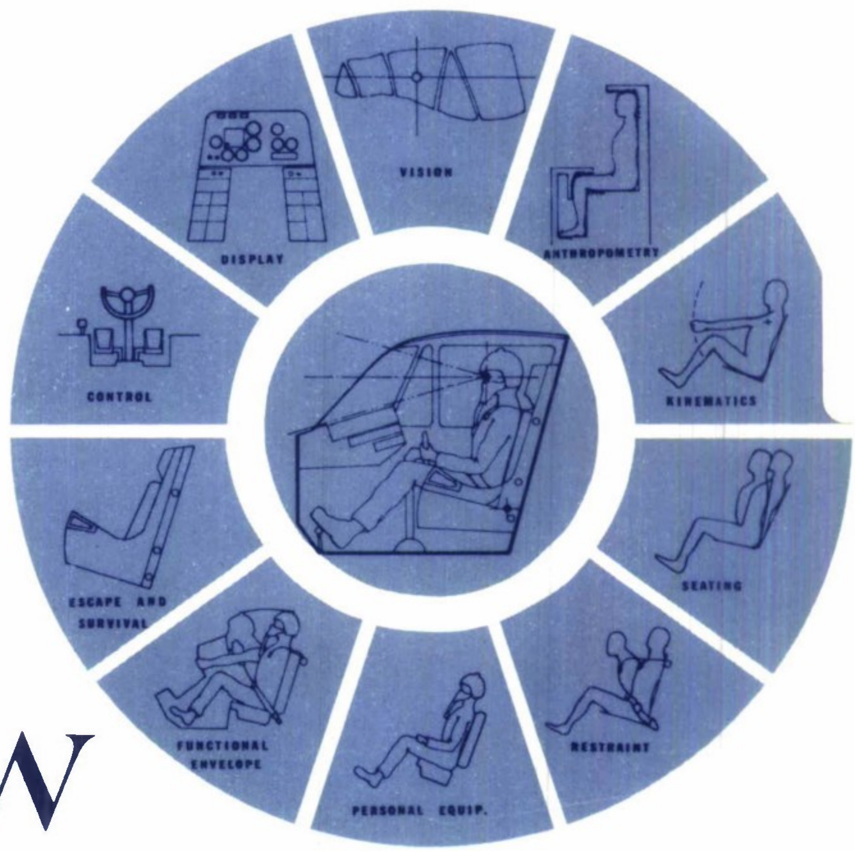

CREW SYSTEM DESIGN

AN INTERAGENCY CONFERENCE

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CREW SYSTEM DESIGN

Edited by

KENNETH D. CROSS

JAMES J. MC GRATH

Proceedings of an inter-agency conference that convened
September 12 - 14, 1972, in Los Angeles, California

Sponsored by the

JOINT ARMY-NAVY AIRCRAFT INSTRUMENTATION RESEARCH PROGRAM

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AEROSPACE INDUSTRIES ASSOCIATION

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SECTION PAGE

SUMMARY

SECTION I

SUMMARY

DR. JAMES J. MC GRATH
ANACAPA SCIENCES INC.

The inter-agency conference that convened September 12-14, 1972, was unique in two respects. First, the meeting had an unprecedented joint sponsorship by the major government agencies with interests in the development of aircraft crew systems, backed by the cooperation and endorsement of the major industries in this field. Second, and more important, the meeting marked the first occasion when representatives of the diverse disciplines that are involved in the crew system design process gathered together under the same roof to discuss their mutual interests and problems. Almost 300 pilots, engineers, designers, scientists, and managers, representing more than 100 different organizations, explored and debated the significant issues of crew system design. This volume documents the proceedings of that conference.

CONFERENCE OBJECTIVES

The purpose of the conference was to promote the timely use of the best available technology in the development and evaluation of crew systems. The need for an inter-agency conference for this purpose was recognized as an outcome of JANAIR efforts to define and assess a broad range of techniques applicable to the design of crew work stations. It was observed that:

- There exists a proliferation of techniques for designing or evaluating portions of aerospace crew systems, but a consolidated definition and appraisal of these techniques has never been made, nor has their proper role in the design process been determined.
- The persons involved in the crew systems design process represent many different disciplines and they do not communicate effectively with each other.
- Some powerful techniques are seldom or never used in practice because their significance is not known to the managers or decision makers.
- A better working relationship and much cross-education is needed among members of the physical, behavioral, and management sciences if optimum crew system design is to be achieved.

The planned conference therefore sought to identify and evaluate the available technology and to foster better interdisciplinary communication in this field. Additional efforts, perhaps a second conference, might later be organized to interpret the significance of this technology for the management of the design cycle. The total objective was to demonstrate that improved crew performance as well as reduced costs can be achieved with the proper blend of management and technology.

RELEVANT TOPIC AREAS

Any topic relevant to the process of designing or evaluating crew systems was considered relevant to this conference. However, the emphasis was on technology rather than on specific system designs. The general questions of interest to the conference were *Where are we? Where do we need to be?*, and *How do we get there?* with respect to the major elements of crew system design and with respect to the integration of the total design effort. The presentations and discussions centered on the specific topics of interest listed below.

CREW STATION CONFIGURATION

Current design approaches to the configuration of crew stations vary widely, and a timely integration of the design approach into the overall system development is often lacking. Moreover, the designer often must work with insufficient guidance from government and contractor management. All too often in the end, a crew station will be developed which does not allow the crew to function efficiently or comfortably owing to a faulty configuration and arrangement of the workspace. Some of the specific topics in this area that were relevant to the conference are listed below.

Geometry

- Application of anthropometric data
- Definition of functional envelopes
- Influence of seating surface and restraint systems
- Use of computer-aided design tools

Arrangement

- Definition of display surfaces
- Placement of displays and controls
- Influence of head-up and multi-mode displays
- Design of multi-crew configurations

Vision

- Location of "design eye" versus "flight eye"
- Influence of advanced displays on vision envelope
- Vision requirements in ultra-high performance vehicles
- Vision requirements for different mission profiles

LIFE SUPPORT SYSTEM

The impact of the life support system on the configuration of the crew station is reflected basically in the equipment that must be installed in the station and on the man. Therefore, the choice or design of a life support system must be an integral part of the crew system design, and a variety of equipments and problems must be taken into account. Some of the specific topics relevant to this area are listed below.

Personal Equipment and Environment

- Pressure suits, survival vests, personal armor
- Restraint and support system
- Services disconnects
- Sustenance and relief facilities
- Rest facilities
- Crash survival equipment
- Impact on comfort, mobility, vision, and performance

Escape and Descent

- Ejection seat concepts
- Crew module concepts
- Discretionary descent concepts
- Clearance envelopes
- Impact on comfort, mobility, vision, and performance

Survival and Recovery

- Need for an integrated survival system
- Experiences in Southeast Asia
- Advanced concepts for recovery systems

CREW STATION LIGHTING

Prior to the introduction of integrated information display systems, the main problem in crew station lighting was that of achieving the proper level of ambient illumination and instrument legibility. However, with the advent of more complex display systems the problem has been greatly complicated by the need for lighting logic. Some relevant topics in this area are listed below.

Basic Illumination

- Crew station ambient illumination
- Panel lighting
- Integral instrument lighting
- Electroluminescent/CRT displays

Information Lighting

- Advisory/warning lighting systems
- Lighting and switching logic

OPERATOR PERFORMANCE

The measurement and analysis of human performance is fundamental to the crew system design process, from the assessment of selection and training requirements to the evaluation of system effectiveness. Nevertheless, a consistent shortcoming has been the failure to obtain and apply the right performance data at the right time. In some instances, the necessary data simply were not available; in others, the data were available but used in an invalid way; in yet others, available and valid data were overlooked or deliberately ignored. Some of the specific topics in this complex area are listed below.

Performance Data Requirements

- Methods for deriving data requirements
- Assessing the existing data base
- Defining the crew's role in the system
- Defining the relevant performance elements
- Establishing performance criteria
- Establishing priorities of data acquisition
- Concepts for performance data banks

Measurements and Analysis Methods

- Subjective versus objective techniques
- Laboratory versus field test techniques
- Generic versus ad hoc task performance
- Establishing appropriate levels of simulation realism
- Subject population and performance sampling
- Measuring complex task loading
- Measuring performance degradation over time

Analysis of performance tradeoffs
Analysis of functional relations between variables
Mathematical models of human performance

Application of Performance Data
Practical problems in using performance data
Problems in applying military specifications
Use of data handbooks and design guides
Formats for reporting performance data
Data extrapolation techniques
Validation procedures

DISPLAYS AND CONTROLS

A capability to harness the remarkable advances in the technology of display and control devices to serve the needs of the crew is seriously lacking. This shortcoming in the system design process becomes more apparent as vehicles become more complex because the crew must process more information and control or monitor more system functions and have less time to do it. The crew member must be given the information he needs, when he needs it, in a form that exercises his decision-making attributes, and he must be given effective controls to properly execute his decisions. Some specific topics relevant to this area are listed below.

Requirements
Methods for establishing display/control requirements
Mission and task analysis techniques
Determining what to mechanize versus how to mechanize
Determining accuracy, reliability, and versatility requirements
Methods for validating requirements

Media
Impact of new developments in display/control technology
Impact of multi-mode display techniques
LED, EL, plasma, crystal matrix, laser-holographic display media
Head-up versus head-down display concepts
Control sophistication versus display augmentation
Principles and techniques of display/control integration
Human factors limitations and standards
Myoelectric, voice-command, and other control concepts

Evaluation
Techniques for assessing individual instruments
Techniques for assessing groups of displays and controls
Techniques for assessing total display/control systems

COST-EFFECTIVENESS OF CREW SYSTEM DESIGN

All crew system designs must ultimately be evaluated in terms of a criterion that balances the system's effectiveness against its cost. Yet there is scant agreement on how to measure "cost-effectiveness" and no one seems to know exactly what it really means. Too often it is taken to mean cost alone. One task of the conference was to examine the issues involved in measuring, interpreting, and applying the cost-effectiveness criterion in the evaluation of crew system designs. Some relevant topics are listed below.

Measurement
The cost elements and their measurement
The effectiveness criteria and their measurement
Quantifying and correlating the variables
Defining the mission/life-cycle measurement context

Analysis and Interpretation
Analytical models of cost-effectiveness
Automation of cost-effectiveness analysis
Interpreting figures-of-merit and other indexes

Application
Practical problems in applying cost-effectiveness data
Empirical validation of cost-effectiveness data
Extrapolating to future systems

Obviously the conference could not deal with all of these topics in depth and, since interaction is the rule in crew system design, the topics could not be treated as independent issues. Therefore, the conference mainly aimed at illuminating the pivotal issues in the topic areas and defining the role of these issues in the total crew system design process.

PROGRAM

The format and program of the conference were developed in meetings of a multidisciplinary steering committee. The conference centered around the following activities.

INTRODUCTORY ADDRESSES

CDR John E. Hammack, the conference chairman, called the meeting to order with a welcoming address. Dr. Hylan B. Lyon, representing the Executive Office of the President, conveyed a message to the conference participants from Dr. Edward E. David, Jr., then Science Advisor to the President. These speakers were followed by Arthur S. Romero, recently retired manager of crew

systems design for the McDonnell-Douglas Corporation, who delivered a keynote address on the crew system design process.

OVERVIEW ADDRESSES

Eight invited speakers then addressed the general assembly. They presented a series of overview papers summarizing and highlighting the pivotal issues in each of the main technical areas relevant to the crew system design process. The speakers and their topics were the following:

- Anthropometry and Kinematics in Crew System Design by Mr. Kenneth W. Kennedy, USAF Aerospace Medical Research Laboratory
- Human Performance Data Requirements and Measurement Methods by CDR Robert J. Wherry, Jr., Naval Air Development Center, Warminster
- Development and Use of Human Performance Data for Design by Dr. David Meister, Army Research Institute for the Behavioral and Social Sciences
- Controls and Displays in Crew System Design by Mr. John H. Kearns, III, Air Force Flight Dynamics Laboratory
- Illumination and Lighting in Crew System Design by Mr. George W. Godfrey, North American Rockwell
- Impact of Life Support Systems on Crew Station Configuration by Mr. E. R. Atkins, Vought Aeronautics Company
- Crew Station Configuration and Workplace Arrangement by Mr. Wolf J. Hebenstreit, The Boeing Company
- Assessing the Cost Effectiveness of Crew System Design by Dr. Raymond E. Bernberg, Litton Systems, Inc.

A discussion period followed each overview address. These discussions were tape-recorded and then edited. They are published in the *Discussion Abstract* section following each overview paper. The published discussions include the comments made from the floor of the general assembly and those which participants submitted in written form.

OPEN FORUM

When the overview papers had been presented and discussed, the speakers formed a panel on the stage and an open forum discussion was held. During this period the floor was open for brief addresses by any participant on any subject germane to the objectives of the conference.

WORKSHOPS

The general assembly recessed during the afternoon of the second day and the morning of the third. The participants convened during these periods in seven workshop groups, chaired by the overview speakers. The workshop topics were the following:

- Human performance data requirements and measurement methods
- Practical application of human performance data
- Crew station configuration and workplace arrangement
- Controls and displays in crew system design
- Illumination and lighting in crew system design
- Life support systems influence on crew station configuration
- Evaluating the cost-effectiveness of crew system design

The chairmen were assisted by multidisciplinary guidance committees in developing the programs of their individual workshops. Each group proceeded in a fashion somewhat different from the others. In some workshops, formal papers were delivered, followed by roundtable discussions; in others, the discussions centered around key issues and questions that had been prepared by the chairman and his guidance committee. The proceedings of the workshops were tape recorded. Edited selections from these recordings are presented in the *Workshop Highlights* sections.

SUMMARIES BY WORKSHOP CHAIRMEN

On the afternoon of the third day the general assembly reconvened. The chairmen of the workshop groups presented brief oral reports summarizing the findings and conclusions reached by their groups. These oral reports were recorded and edited for publication.

CLOSING ADDRESSES

The final session included an informal address by Mr. Romero summarizing his assessment of the extent to which the conference achieved its objectives, and followed by closing remarks by the chairman and representatives of the sponsors of the conference.

CONFERENCE THEMES

Several weeks after the conference adjourned, a review committee convened. The committee, comprising the conference chairman, the editors, and several of the workshop chairmen, reviewed the unedited proceedings of the conference to determine how the findings might be summarized. The issues that were addressed by the participants in the conference were found to be numerous and complex. The committee concluded that specific issues or recommendations could not be abstracted meaningfully from the contexts in which they arose, and that we had best let the participants speak for themselves in the main body of this report in presenting their points of view and recommendations. Therefore, instead of preparing a listing of conclusions and recommendations the committee identified the major currents or themes that ran through the conference, cutting across specific topic areas and addressed independently by different workshops or speakers. We believe that these themes, better than any abstracted list of specific findings, summarize the pervasive issues of crew system design.

TOTAL SYSTEM DESIGN

A consistent theme throughout the conference was the need for a total system approach to crew system design. This need, in part, motivated the organizers and sponsors of the conference in the first place, and was expressed by Mr. Romero in his keynote address. Speakers and workshop discussants described numerous specific problems caused by a piecemeal approach to crew system design and recommended ways to bring about an integrated design effort. The need for integration of design was expressed at two levels. First, the components of the crew system must reflect an integrated design because they interact. The interaction of crew system components was particularly emphasized by the workshop on controls and displays, and the workshop on illumination and lighting. Second, the crew system as a whole must be integrated with the total design of the vehicle or weapon system. The interaction of the crew system design and the total vehicle/weapon system design was emphasized by the workshops on life support systems and crew station configuration. In a larger sense, speakers throughout the conference stressed the principle that crew system design, in its many facets, cannot be undertaken in isolation and that the major need is for action that will enhance the integration of design efforts. Furthermore, this integration of efforts should be reflected in the managerial structure of the procurement and production organizations.

INTERDISCIPLINARY EFFORTS

Whatever the specific topic under discussion, the workshops and speakers pointed to the need for interdisciplinary efforts in the design process. Usually, emphasis was placed on the need for better communications among the system designers, operators, and managers--a need that was to some degree served by the conference itself. But better lines of communication alone will not suffice; a positive coordination and cooperation of efforts must be achieved. For example, the workshop on illumination and lighting pointed out how coordination of the efforts of the lighting engineers and the airframe designers would avoid such severe problems as reflections on the canopies and windscreens. Problems were described by other discussion groups that stem from the lack of coordination between procurement agencies, between a procurement agency and the contractors, and between groups within the procurement agency and within the contractor's organization. In particular, recommendations were made for improving the lines of communication and cooperation between the designers and the users of crew systems.

TIMELINESS OF INPUTS AND ACTIONS

Much of the need for improved interdisciplinary efforts was reflected in the participants' descriptions of problems that arise from the scheduling of tasks and events in the design process. Some problems occur because inputs or actions come too early in the design process. For example, the lighting mockup review takes place too early in the development cycle (typically 120 days after contract). Sometimes more than half of the lighted equipment that will eventually be put into the cockput has not yet been developed or procured at the time of the lighting mockup review. Other problems occur because inputs or actions come too late. The need for human performance studies is often recognized too late to permit the data to be collected and used effectively. Too often, cost-effectiveness evaluations are made when there are few choices left and only a take-it-or-leave-it option remains. Several speakers pointed to the need for concurrent actions or decisions by different groups in the design process, reflecting again the need for interdisciplinary coordination of efforts.

STANDARDS AND SPECIFICATIONS

The issue of standardization is joined in any discussion of design procedures, and predictably that issue was addressed in various ways by many speakers and discussion

groups. At one level, the point at issue was the concept and role of standardization in crew system design. Some participants felt that standardization often precludes design innovations where innovative solutions are most needed and that Military Standards do not allow sufficient freedom for the designer. Other participants felt that many problems in crew system design occur simply because existing standards, such as those dealing with instrument arrangement, are not properly followed. A controversial issue was whether or not standards should be applied only to hardware characteristics, such as the size and location of a display, leaving the software characteristics, such as the display's symbology, to vary as needed to satisfy the requirements of different users. At another level, Military Standards and Military Specifications were questioned in terms of their adequacy, validity, and appropriate level of specificity. Participants considered that some Military Standards and Specifications are mutually contradictory or incompatible, many are based on anachronous requirements or technology, and few are cast in a manner that will facilitate integrated designs. Specifications calling for the use of Government Furnished Equipment particularly limit the designers' ability to develop a fully integrated system.

OPERATIONAL REQUIREMENTS

The participants in this conference were keenly aware of the importance of statements of operational requirements as the foundation for crew system design. Across the spectrum of topic areas the questions were raised: What constitutes a "requirement?" Who is responsible for stating a requirement? How should statements of requirements be developed and to what degree of specificity? How can requirements be validated? How can they be translated into design options? Underlying the discussions of these issues was a recognition of the need for flexibility in crew system design so that the systems can be economically adapted to changes or differences in operational requirements. In the workshop on controls and displays, Mr. Wolin went a step further, "Recognizing the individual differences among pilots, both in abilities and preferences, we believe the display systems should be programmable not only to provide the information required for different missions, but also sufficiently flexible to accommodate these individual differences." While some participants declared that statements of operational requirements are not specific enough to guide the crew system designer, the more general view was that requirements often are not stated in the proper terms. The prevailing view was that the customer or user should indicate the required capability and let the designers or engineers determine the means for achieving that capability.

HUMAN PERFORMANCE DATA

The measurement of crew performance and the application of performance data to crew system design were formal topics of two workshops, but were also general themes of discussion throughout the conference. The need for human performance data in crew system design was broadly accepted by the participants, and much of the discussion focused on ways to obtain relevant data in time to put it to effective use. One point was made clear: if human performance studies are to provide relevant, timely data, they must be conducted very early in the design process. In addition, separate programs must be funded and conducted to provide a continuing source of performance data for future requirements. However, in most of their recommendations dealing with the development of adequate human performance data, the speakers and workshops were quietly vague in specifying who should be responsible for data development efforts. Design engineers maintained that only system-specific performance data are truly useful, yet they insisted that neither time nor funding can be allocated to develop such data once the design process begins. The main issue with regard to human performance data might not be the question of what data are needed, but who should be responsible for providing the data to the crew system designers.

RELATING DESIGN TO PERFORMANCE

Some of the strongest recommendations and most heated debates were aimed at the fundamental need to demonstrate, with quantitative evidence, the relationship between system design and system performance. The issue is far more complex than it might appear on the surface. Properly controlled studies of the relationship between design and performance are hardly ever feasible, and oversimplification is the rule. The participants further noted that only the negative, performance-degradation aspects of the relationship are typically emphasized in decision making, and that we must seriously try to establish the positive, performance-enhancement aspects of the relationship. For example, when the negative aspects are emphasized, designers tend to over-automate crew systems, which in turn leads to a large loss in cost-effectiveness. One reason for this tendency to over-automate is that the probability of human error is typically overestimated while the probability of equipment error is underestimated. Many recommendations were made for studies and procedures to establish quantitatively the cost of poor design, but more especially the benefits of good design. However, as noted above, no clear assignment of responsibility for funding or conducting such studies was proposed.

INFLUENCING MANAGEMENT

The problem of relating design to performance was at the heart of another theme that ran through the conference: selling it to management. Some participants asserted that program managers in industry and government will readily accept design recommendations when they are backed by relevant data; others have found in their experience that exaggerated case-making tactics are necessary; yet others have found that they must often resort to emotionalism because merit alone will not always suffice. Designers, operators, and scientists also expressed dismay or consternation at their frequent exclusion from the decision-making process. Although some participants felt that the problem was to change the attitudes of some program managers, most of the participants emphasized the need to develop better methods of assessing the costs of crew system design options and more quantitative procedures for establishing the benefits of those options.

TEST AND EVALUATION

The techniques and criteria for testing and evaluating crew system design were subjects of discussion in most of the workshops. Severe criticisms were leveled at the conventional cockpit review as an evaluation technique, while considerable endorsement was given to the use of dedicated aircraft in the test and evaluation of crew systems. However, participants in this conference were generally more concerned with assessment criteria than with assessment methods. They questioned the bromide that total system performance is the ultimate criterion in evaluating crew system design. Total system performance does not necessarily reflect crew performance. Also, if the system is well designed it will be insensitive to the degradation of its subsystems; therefore, total system performance will be an insensitive criterion of subsystem performance. Recommendations were aimed at improving the representativeness of the crews, tasks, and measurements used in test and evaluation procedures.

FORECASTING THE FUTURE

Although past mistakes and present problems were discussed at length, the need to forecast and respond to future systems and technology was also a central theme in the various workshops. This theme was expressed in terms of the need to provide for the growth of present systems, to anticipate new requirements or changes in the operator's role, and to extrapolate from the existing data base to crew systems not yet designed.

ACKNOWLEDGMENTS

This conference, like any large interdisciplinary meeting, required the efforts of many individuals and organizations. The key personnel have been acknowledged at the beginning of this report (p. ii), but on behalf of the conference sponsors, I would like to take this opportunity to give special thanks to a few of these individuals.

Dr. Hylan B. Lyon, formerly Chairman of the JANAIR Committee, was largely responsible for the conception of the conference and for marshalling inter-agency support if it. CDR John E. Hammack, his successor, guided the organizing efforts and ably chaired the general assembly of the conference. E. R. Atkins, Wolf J. Hebenstreit, and Arthur S. Romero were instrumental in defining the conference's objectives and format, and they participated in the post-conference review. Their efforts are highly commended and the contribution of their time and talents is sincerely appreciated.

INTRODUCTORY REMARKS

SECTION II

CALL TO ORDER
CDR JOHN E. HAMMACK
JANAIR CHAIRMAN, OFFICE OF NAVAL RESEARCH

On behalf of the sponsors of the Inter-Agency Conference on Crew System Design, I welcome each of you. A conference of this stature has long been talked about. It represents the first concerted attempt to promote the timely use of the best available technology in the development and evaluation of crew systems. The members of the conference steering committee are impressed with the talent that is present and with the diversity of organizations represented. We are grateful for this talent because it represents the potential to achieve the conference objectives.

My particular experience with crew systems has been gained in the cockpits of several military tactical aircraft under conditions varying from total boredom to stark, raving terror. My evaluation of the design of some cockpits has been less than complimentary. So, I welcome the opportunity to charge this group with the responsibility for improving the design of crew systems. Many of us have problems that need resolution now, but we must not forget our obligation to the operators of future airborne systems and to the managers who will procure and evaluate those systems. Let us take advantage of these three days of conference to mark the way to better crew systems.

WELCOMING MESSAGE
DR. HYLAN B. LYON
EXECUTIVE OFFICE OF THE PRESIDENT

It is a pleasure to welcome you all to this conference. I want to take this time to share some thoughts on the objectives of this conference from the perspective of the Office of Science and Technology in the Executive Office of the President. Dr. Edward E. David is the Science Advisor to President Nixon, and he is concerned with a broad range of issues to assure that science and technology are used most effectively in the interests of national security and general welfare. I apprised Dr. David of this conference and of the contribution that it could make to efficient aerospace vehicle design. Whether you are interested or not, you are in the spotlight right now. The next five years may be a turning point in the United States aerospace industry and this meeting could play a significant role in the unfolding history of this industry. I am pleased to read a statement to you from Dr. David.

> "As you face the future and the problem of designing complex man-rated systems, you should be concerned more than ever with optimum system performance and the effects of the human element on this performance. The human element has been recognized for years as an integral part of effective system design, and many different approaches have been attempted to characterize the human response function. We all know that there is still a long way to go before the design decision-making process can properly incorporate human performance. This is especially true with crew system designs which enter into the early design tradeoffs with the propulsion, structures, and aerodynamics disciplines. This conference recognizes the need for an assessment of the state of the art of the technology in crew systems design. This is a timely and a necessary goal. The attempt to consider all aspects of human design requirements is to be commended. However, do not forget your stated goals, especially those of identifying significant techniques, and developing better relationships between the many diverse disciplines represented at the conference. You have a big job ahead of you and it will require your best efforts."

One of the many interesting aspects of Dr. David's responsibilities is understanding the factors that affect the flow of technological information between the many government agencies and the civil sector. This becomes an issue especially when different agencies have similar requirements and efficient

funding is a matter of concern. However, if you are to bring your technology into the design cycle you must move into the area of effective management. You must aggregate the effects of the many contributing design factors and relate them to dollars. The dollar is a strong motivating factor in the design cycle.

Many conceptual changes in aircraft design coming down the pike will require a more effective strategy of crew system design than the best you could come up with today. I will mention a few as examples: automatic flight, vertical takeoff and landing, collision avoidance, side force control, active control, fly by wire, airframe integration, optimal flight path, cockpit ejection, and many others. We are in a new ballgame, because these and other factors make the extrapolation of our past experience in building aircraft much less useful in defining the next generation system. Yet, without the benefit of guidance from past experience, we stand in danger of making monumental and costly mistakes. Through cooperative efforts such as you are attempting at this conference, we must arrive at a better assessment of future system requirements while our options are still open.

I have been involved with planning this conference since 1969 when Leo Hickey of the Boeing Company tried to unfold for me the manifold problems of getting the various disciplines to work together in creating a good cockpit design. I have been growing during this period and my perspective has changed. If you ask me how it has changed, you will get one of the two-hour tirades which some people got last night. I could offer many possible answers, but the best might be this: a few years ago, I thought it would be very good management to create an efficient strategy of crew system design; but now I think it is absolutely critical. We must get together and determine objectively what must be done. We must determine how close we are to having the answers we need. We must define what improvements are required. We must accomplish these objectives, and the sooner the better.

THE CREW STATION DESIGN PROCESS

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Abstract: *In the crew system design process, man provides one or more of the functional links and must be considered an integral component of the system. In designing for the optimum configuration for operator efficiency, the design process combines the knowledge and experience of several scientific disciplines. Despite these interscience contributions, it is common knowledge that the crew station configurations vary widely in arrangement and geometry. Unsatisfactory configurations have resulted from the misuse or misunderstanding of human physical and behavioral data with the result that the comfort and mobility of the operator were greatly reduced. To achieve the optimum configuration of the crew station, new methods must be developed for establishing requirements and evaluating the arrangement; otherwise the age-old system of evaluation by operator opinion will continue.*

INTRODUCTION

Although man has made attempts to fly for centuries, it was just a little less than 69 years ago that true controlled, powered flight was achieved. As would be expected, the first airplanes to fly comprised a minimum of components. As time passed and the possibilities of the airplane became more evident, the airplanes increased in complexity. This complexity required more time for design, development, and testing of the components. The cost of production increased accordingly. The time and cost to produce future designs that must satisfy both the engineering requirements and the human operator requirements will demand critical consideration throughout the design process.

The crew system design process is a precise approach for combining the knowledge and experience of several scientific disciplines in the design of equipment and work areas that must incorporate the optimum combinations of human and physical components in any vehicle, whether it is operated on the land, underwater, in the air, or in space. This inter-agency conference will address itself primarily to the design of the crew station of the military airplane.

DEFINITION OF A SYSTEM

If an airplane is to perform a useful function, it must be designed as a system. Today's aircraft, military and commercial, can

be likened to the human organism: a highly complex structure with parts so integrated that their relationship to one another is governed by their relationship to the whole. A system, therefore, is a group of components arranged in such a manner as to satisfy a specific set of requirements. These requirements must be devoid of ambiguity because basically they will define the mission that the system will perform. In the aircrew system design process, the term *system* is construed to mean not only the hardware and equipment components, but also the human who will operate these equipments. Man, therefore, provides one or more of the functional links in the operation of the vehicle, in addition to monitoring individual systems and controlling the overall system. This interaction between man and machine in performing a mission is defined as a man-machine system.

Unless it is our intent to design machines that are entirely automatic, man must be considered an integral component of the system. As such, his performance is as vital to the successful completion of the mission as any of the systems components.

Today we are assembled here to ask ourselves, "Where are we, where do we need to be, and how do we get there?," with respect to the major elements of crew system design and with respect to the integration of the total design effort.

ELEMENTS IN CREW SYSTEM DESIGN

The growth of science and technology in this century and in particular during and since World War II has brought forth unbelievable advances that have had a greater impact on the lives of more people in more numerous ways than has been recorded in the history of the world. But man, who by the grace of God has acquired the technical knowledge to accomplish these outstanding advances, alone remains unchanged in his remarkable world. Regardless of this fact, man is the most important component in the man-machine concept because he can discriminate when confronted with an unforeseen situation and he alone can take corrective action. However, to ensure that he will be alert to the emergency, should it arise, design care must be exercised in providing him with the proper environment.

In order to achieve the proper environment, with which we here are concerned, we must consider the many design disciplines that contribute to its development. Included is the anthropometry and kinematics of the crew station operators; the geometry of the crew station configuration defining the envelope in which the operator must function; vision inside and outside of the crew station; the life support system which comprises the equipment that must be installed in the station and on the operator, including the personal equipment which must be worn by the operator and which often places a constraint on his ability to function, his seat and restraint systems, and the escape, descent, survival and recovery systems; overall illumination of the station, lighting of the instruments, consoles and displays, and information lighting such as warning and caution signals. Avionics, a relatively new discipline, is having a tremendous impact on the crew station configuration. Finally, human factors considerations, including the measurement of human performance and its application to crew station design, are central to the design process.

OPTIMUM SYSTEM DESIGN

Because no single mind can comprehend all of the knowledge embodied in these specialized design technologies, the one-man approach, under the direction of the Chief Engineer, who knew every detail of the job and directed its design and development, has been replaced by a new approach called systems engineering. This approach endeavors to achieve an orderly completion of complex programs by organizing all of the separate functions into an integrated whole. Each program is headed by a Program Manager, who is a rather glorified combination of the once absolute dictator--the Chief Engineer--and his frustrated subordinate--the Project Engineer. The Program Manager is supposed to make certain that his project is staffed with specialists from all disciplines that will contribute to the design process such that the successful completion of the program is assured. I believe it is safe to say that most Program Managers know very little of the details of each specialist's work. However, he should be knowledgeable about the overall design requirements of his program and understand the importance of the interscience relationships such that he can coordinate and direct all efforts toward a timely and cost-controlled completion. In this respect he is striving for the optimum design.

It follows, therefore, that achieving the optimum system design means producing the most economical solution to a given set of requirements. The system thus produced will be the smallest, lightest, and simplest system that will satisfy all of the requirements. Because of these virtues, it will be the least expensive.

Essentially, there are four basic areas of design in an airplane: aerodynamics, structures, propulsion, and control. Tremendous technical advances have been made in each of these specialized fields. But what about the design of the aircrew station, the command post which is the terminus of the avionics and mechanical controls responsive to these four basic areas, and how does it fit into the

design process? The pilot's station, or cockpit, of the early airplanes incorporated a stick, seat, rudder bar, and very little more in the way of instruments and controls for operation of the vehicle. The pilot's station in today's airplanes still employs the stick, seat, and rudder pedal arrangement. Despite the fact that many believe the present-day aircrew station is the functional outgrowth of almost 69 years of development, it is in reality a crowded cubical housing the maze of instrument, handles, and switches required to navigate and control the vehicle and to release and guide its weapons to the target. Why should this continue to be?

Many reasons for this are given, but very few are valid. Quite a few years ago, a cartoon circulated throughout the aviation industry which many of you may recall having seen. This cartoon depicted part of the problem quite well. It pictured the airplane as visualized by the many design specialists involved in the design process. For example, the aerodynamic specialist pictured a streamlined body devoid of all protuberances; the structural engineer saw his contribution as two massive crossed I-beams; while the propulsion specialist saw only a huge engine to which was attached a microscopic aircrew station. Each design discipline saw its specialty as the most important to the overall design.

From the earliest airplanes to those that saw service in World War II, the aircrew station seemed to occupy the last vestige of space within the fuselage after all other requirements had been satisfied. Man, being an articulating organism, was squeezed into this remaining space to operate the vehicle to the best of his ability. Prior to World War II, those operators experienced only minor difficulty in giving adequate attention to the operating requirements of their vehicles. Towards the end of World War II, however, the airplanes were becoming more complex and the operator was required to do more tasks in less time in order to keep his vehicle performing. Accidents increased and men and machines joined the lists of statistics. Although the performance of the machines was being improved steadily, little, if any, consideration was being given to man and the limitations of his capability.

It was not until after World War II that a specialized approach to information about man began to be developed to consider how to design safety and functional efficiency into a man-machine system. This specialized approach is known as human factors in the design process. In order that this specialized approach could be effective in the design process, the aviation industry began to bring personnel from the behavioral, medical, and social sciences into its engineering departments. Thus the design procedure was to be that of the team specialist approach.

Despite the influx of specialized disciplines into the engineering effort, it is common knowledge among designers and aircrew personnel that the aircrew stations in which the latter must function vary appreciably in arrangement and geometry. It is evident that we have failed to produce the optimum design in the aircrew station, otherwise we would not be assembled here today.

IMPROPER APPLICATION OF DESIGN DATA

Marginal and totally unsatisfactory aircrew station configurations have resulted from the improper application of design data or the use of obsolete information. An example of this is the case of developing the human functional envelope using obsolete anthropometric data. Design an aircrew station for a given population whose body measurements were the accepted standard 20 years ago, when the vehicle being designed is to be operated by individuals coming of age five to ten years hence, and the result will be anything but optimum. This is not the fault or responsibility of the anthropometrists, but of the budgeteers who do not recognize or understand the need for these data in the design process. Anthropometric measurements are those of the nude body and often are used as basic geometry without proper consideration of the special clothing and personal gear that will be worn by the aircrews. These personal equipment items modify body dimensions and impose constraints on body movements and do affect the basic geometry. The pressure suit, for example, when inflated has a profound effect on the "design eye" and "flight eye" positions, on the functional reach, and on the volume of the functional envelope.

The design engineer must be alert to the geometric effect of "operator slump" on the design ard flight eye positions. Anthropometrists measure the erect human in the "military attention" position and the seated human in the "seated attention" position. Human beings do not remain in those positions much of the time. Look around at your neighbors.

In the design and development of aircrew work places, particularly of the seated operator, the design engineer needs anthropometric and kinematic data for the population that will be assigned to those work places. Military vehicles and equipment designed for the United Stated Armed Forces are being used in many instances by personnel of foreign military forces. Variations in their comparative anthropometry to that of United States military personnel have resulted in difficulties in operating the vehicles and equipment. It is, therefore, vitally important that valid

current anthropometric and kinematic characteristics of the aircrew population be understood by the design engineer and that these data be in a format that is relevant to design.

INTERDISCIPLINARY MISUNDERSTANDING

The engineer is fundamental to good design and he exerts tremendous influence in achieving the optimum design. His prime objective in this respect is to optimize the performance of the machine. This, of course, can only be achieved if intelligent consideration is given to the numerous factors that affect the design process. In this regard the design engineer is under continual pressure to meet program milestones and production schedules. Under such pressure he will proceed to analyze the physical requirements--electrical, mechanical, or structural--in terms of function, size, weight, and cost with respect to the total system. He will review specification requirements in great depth and will outline in detail the design parameters. He will consider the mission requirements and prepare trade studies to determine the optimum components and their function. In these efforts the design engineer is basically responsible for the application of human factors principles, but the manner in which these data are applied, if at all, is not self evident.

In a system that combines man and machine it becomes necessary, although at times most difficult, to determine how to divide the work. It is in this preliminary phase of the design process that the efforts of human factors engineers, who are primarily psychologists, should be directed toward the application of information about man, his capabilities and limitations regarding the operation of machines, and the environment in which man will operate those machines. In an endeavor to obtain answers to those questions of man's behavior and his capabilities and limitations under varying conditions, it was natural to turn for assistance to the science of general and experimental psychology. Unfortunately, most of the specialists in this discipline had about as much knowledge or experience in the sciences practiced by the design engineers as the design engineer had in the sciences practiced by the psychologist. Consequently, mutual understanding and communication across this interscience interface presented problems.

One reason for this is the difference in interest among human factors specialists. One group, the researchers, are interested primarily in just that: research. Another group comprises those who are interested primarily in the application of human factors principles in engineering design. Those interested in research are interested in the solution of specific problems related to individual parts of a system. In many instances, the research type may not understand the application of human performance data to specific engineering needs in system design. In such cases, the need is for a behavioral scientist trained in the application of human performance principles to the total system concept. Only in this way can we be assured that human performance data will be incorporated in the preliminary design process to achieve the optimum design where man is a functional component.

CREW STATION CONFIGURATION

The development of the aircrew station configuration demands serious consideration by the design engineer because it is in this preliminary design phase that all of the technologies that contribute to the configuration of the aircrew station manifest themselves. Particular attention is required for the integration of the life support and avionics requirements because of their effect on the comfort, mobility, vision, and performance of the aircrew. Complications for the engineer often result from ambiguities and incompatibilities between standard requirements and design specifications. The latter is the principal source of information for the design engineer and he will consider the total requirement for the vehicle, its operational crew, the mission, and the environment in which the mission will be performed. This means that the engineer needs more information than is presently obtained from the mission and task analyses.

The ultimate design is the outgrowth of compromise. The ability of the engineer to determine what to mechanize as well as how to mechanize requires him to compare configurations that involve not only the physical requirements but the behavioral requirements as well. Here again the engineer needs human performance data in a format that is relevant to design. Without such data and some scientific approach to evaluate the basic and alternative configurations the age-old method of evaluation by operator opinion is going to continue.

If cost effectiveness is to be achieved from the standpoint of the crew station configuration we must clearly understand the total problem. It is essential that we develop methods for establishing requirements and evaluating the arrangement. It is also essential, therefore, that a methodology for such cost-effectiveness measurement must utilize human factors inputs to measure effectivity.

Each new weapon system that has emerged from the drawing board has presented more difficulty in the development and arrangement of increasing numbers of control/display components. Although these displays are intended to assist the pilot in the operation and

navigation of the vehicle, almost the opposite effect is occurring. The operator is being given more and more information and less and less time in which to use it.

This is where we are in the crew system design process today. This is where we were 27 years ago at the close of World War II. Where do we need to be and how do we get there? These are questions that we hope to resolve, in part at least, as a result of this conference. The overview papers to be presented by the other members of this panel will generate some thought-provoking information on several crucial areas in the crew system design process.

In closing let me repeat that the increasing complexity of the airplane is requiring more time for design, development, and testing of the components. The cost of production is increasing accordingly. If we here are to achieve our goal we must remember that the time and cost to produce future designs that must satisfy both engineering and human operator requirements will demand critical consideration and cooperation from all disciplines throughout the design process.

HUMAN PERFORMANCE DATA REQUIREMENTS AND MEASUREMENT METHODS

SECTION III

HUMAN PERFORMANCE STUDIES FOR THE AIRBORNE CREW STATION DESIGN PROCESS

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Abstract: *The difficulty of estimating the overall effect of each crew station design decision on operator performance is discussed. Closer following of human engineering principles derived from human performance studies is advocated. It is pointed out that airborne operational situations present unique crew station design problems. The necessity for accomplishing additional and more relevant human performance studies for rapidly developing advances in a variety of technological areas is emphasized. The need for better definition of objectives, inclusion of more relevant variables, closer examination of ways to present variables of interest, and use of more sophisticated data analysis methods for human performance studies is discussed.*

INTRODUCTION

This session will discuss the measurement and analysis of human performance as it relates to the crew station design process. During the crew station design process there would seem to be only one reason why human performance data would be collected. That reason is that we cannot accurately predict what the effect of the multitude of crew station design decisions will be on the operator's performance. Some have advocated the use of human performance data banks to help alleviate this problem. Such data banks are depositories of human performance data collected from numerous studies and stored for later retrieval. The type of information stored is typically the speed and accuracy of accomplishing a particular task. Thus, if a decision is made to allocate a particular function to an operator, the data bank information can be used to estimate how well that function will be performed. However, even if we could estimate what the probable effect on each crew station decision would be on the operator's performance, we could still not say whether, overall, the decision was a good one or not, for while crew station decisions are made one at a time, the operator must live with them in toto. The design process itself neglects this overall context in which a particular task will be accomplished in the new crew station. If one asks a question like, "How accurately can an operator perform task 'x'?," the information stored in the data bank may be misleading inasmuch as it may have been derived from operators who were much more or much less busy than the operator in the new crew station will be. The data bank approach doesn't seem to fully account for the adaptive nature of human performance.

Often an individual crew station design decision, even though it has not followed good human engineering principles, cannot be positively indicated as definitively reducing crew effectiveness, but a cumulative reduction in operator effectiveness does result. Considering one at a time, a poor location for a given switch would not jeopardize a mission, but the net result of 50 or more poorly located controls could be disastrous. We must, therefore, somehow predict or be able to quantify what the overall effect will be on the operators of the totality of the crew station design decisions. In part, this is accomplished qualitatively by the use of human engineering guidelines and standards. Human engineering principles are not the result of "common sense" but are derived from earlier human performance studies. Therefore, when a system is designed following human engineering standards and guides, we can be reasonably certain the net effect on human performance will be positive. However, we rarely see a crew station whose design has not badly compromised "good human engineering principles."

UNIQUE PROBLEMS IN AIRBORNE CREW STATIONS

The very nature of the airborne operational situation presents unusual crew station design problems which, in the past, have often precluded the complete use of these "good human engineering principles." Space in the cockpit is at a premium, and displays and controls are often crowded together far more closely than would be allowed following good human engineering.

With requirements for visual contact with the real world, the operator is surrounded by a canopy which does not permit control of ambient illumination. Cockpit displays and labels must be designed for legibility both during nighttime as well as bright daylight conditions, and attempting to satisfy both extremes is not completely possible.

Structural engineering requirements have necessitated the placement of structural supports where we might otherwise have desired to locate a display or control. Weight and power limitations have often prohibited desirable temperature, humidity, and noise control. High-g maneuvers, turbulence, high altitude flight, cold weather survival, etc. have required the use of special head and body restraints, supports, and protective clothing and devices which have encumbered the operator much more than desirable for good human performance. The necessity for rapid egress has, in the past, dictated the use of escape envelopes which have forced the placement of displays and controls out of easy access to the eyes and hands of the operator.

These are but a few of the reasons why good human engineering principles have been disregarded too frequently in airborne crew stations. They have been sacrificed because of engineering and other considerations. Whether such tradeoffs, which have undoubtedly seriously degraded operator performance, really resulted in a better overall system is probably not known. Normally, the opportunity to establish what the effect of these tradeoffs has really been on operator performance and system effectiveness never presents itself.

DETERMINING EFFECTS ON HUMAN PERFORMANCE

It is one thing to be able to say that an airborne crew station should be designed following good human engineering principles. It is quite another to be able to state what the effects on human performance will be if an alternative design philosophy is adopted. But it most certainly should be a necessary endeavor during the crew station design process, for it is not uncommon for the good human engineering suggestion to be disallowed because it is cheaper or easier to accomplish the design some other way. If intelligent tradeoffs are to be made, we must be able to say what amount of degradation in operator performance will follow if the alternative design is accepted.

I believe this is, to a large extent, why human performance data have been collected in static mockups, dynamic mockups, and flight tests; because we are unable, at present, to accurately predict the effect of the various crew station design decisions on human performance. While I cannot prove it, I also believe that, by and large, such studies have had little demonstrable effect on ensuring the optimal design of the crew station.

ARE TRADITIONAL CREW STATION DESIGN TECHNIQUES EFFECTIVE?

This may sound like heresy to suggest that better crew station design will probably not result from fabricating a crew station and collecting human performance data. Consider, however, the following problems with such an approach. First, even to build a dynamic mockup of a crew station in which operator performance data may be collected requires hundreds of crew station design decisions to have been made and, usually, a rather lengthy period to fabricate it. Second, to ensure valid data is collected, we must have operators trained in the tasks they are expected to accomplish as well as trained in the use of the displays and controls they must operate. This, too, takes time. A third consideration is that to be able to generalize to the population of fleet operators, we must collect these data, not on one or two operators, but on quite a few. If not, we most certainly will run the risk of having our operator sample misrepresent those who will use the system in the fleet. Not only would training and collecting data on many operators be very time consuming, but we would have a real logistics problem in convincing the various services to make these operators available for such studies.

Even if the cost of such a series of studies could be ignored (which, of course, it cannot), preparation of the dynamic mockup and the collection of these data would take an inordinate amount of time. Following data collection, we would still have its analysis with which to contend, followed by recommendations for changes in the crew station design. And if we are to prove that the recommended changes are really beneficial, we should modify the fabricated crew station and collect similar data to positively demonstrate the gain in human performance. Such a process would take nearly as long as the original study. Anyone familiar with the present crew station design process will realize that such amounts of time are just not available. All of this discussion is leading toward the

conclusion that human performance studies accomplished during the crew station design process will probably not significantly alter the design of that station. Such studies are highly useful in verifying that the crew station design of that system is at least usable in the fleet. And let me emphasize that this test and evaluation function is mandatory, for we cannot afford to send aircraft with unsatisfactory crew stations into the fleet. But there is a great difference between a crew station which is minimally satisfactory and one that might be described as an excellent crew station. My previous experience in human performance studies during test and evaluation flights is that many discrepancies and deficiencies are always uncovered, but if the system is at least minimally suitable for service use, few changes will be made. This occurs, not because the services do not want excellent crew stations, but because the cost of changing the crew station at that point in the RDT&E cycle is prohibitive. These studies, in addition to certifying that the crew station is at least acceptable, are also useful for gaining information for subsequent improvements in the crew station in future modifications of that aircraft.

THE RELEVANCY OF HUMAN PERFORMANCE STUDIES

Such human performance studies as we have just discussed are highly "system- specific," where one works with the actual or prototype displays and controls, configured as we find them in the actual system; where the type and complexity of operator tasks are those actually required in the fleet; and where, hopefully, the external stimuli impinging on the operator are like those really encountered by that system in the hostile, real world. The results from such studies will not generalize readily to different systems. No general principles of "human performance" or "good human engineering design for airborne crew stations" will be derived from such studies. Little general knowledge will be gained toward understanding the capabilities and limitations of aircrews or what the relationships are among the multitude of variables that occur in a system. For such applications, drastically different kinds of studies must be carried out.

Studies which have as their objective the derivation of human engineering guidelines and standards are continually needed for rapidly developing new control and display technologies. We cannot afford to wait until a system is actually being built to determine how best to interface man with these new displays. Too often in the past the content and format of information to be displayed on new devices has been left to the discretion of avionics engineers rather than being the result of human performance studies which could prove or disprove the validity of various display presentation schema.

Advances in solid state computers with lower power requirements, smaller space and weight requirements, and increased reliability indicate an increasing reliance on computers for integrating incoming sensor information and for accomplishing system monitoring. Again we cannot afford to wait until a given system is being built to determine optimal ways to either use this expanding capability or to interface the airborne operator with his system's computers. Already it is apparent that machine recognition of voice and speech synthesis by computers will be at an acceptable state of the art in the next few years. How such technology can best be applied in airborne situations must be studied and determined now if optimal use of these technologies is to be realized for our next generation of aircraft. Prototype voice recognition and voice synthesis systems must be fabricated and human performance studies must be carried out to uncover difficulties before we attempt to use such systems in aircraft.

Advances in propulsion techniques and structural engineering allow the possibility of exposing pilots and other aircrews to higher g-levels than is done presently. New methods of supporting the crew members must be tried out while they are performing tasks similar to those we may expect of him in the future. The escape capsule is emerging as a truly viable alternative to escape seats. We may anticipate radical departures in airborne crew station design in the early 1980's and we must not wait until then to determine optimal crew station design. We must, for these purposes, accomplish a host of human performance studies. Since we cannot accurately predict man's new role in these systems, we can use generic rather than existing operator tasks in these studies, but we must be careful to ensure they are at least similar to what we expect them to be in the future.

PROBLEMS WITH LABORATORY STUDIES

Merely accomplishing a human performance study does not guarantee that the results will be relevant to airborne crew stations. Many of the human engineering standards that we presently use were derived in what I think was a questionable manner. In the area of legibility, for example, a majority of the studies on which our standards are based presented the stimuli tachistoscopically to the subjects. Choice of optimal letter size, stroke width, font style, etc. were based on accuracy of reported reading under these very brief exposures to the stimuli. From an experimental point of view, the method of stimulus presentation was easy to use in the laboratory. However, I know of no airborne

application in which we present information to an aircrew tachistoscopically. One cannot help but wonder if these data are really relevant. Additionally, from such studies we do not have the necessary tradeoff data which would allow us to estimate what additional reading time will be required by the operator if recommended legibility guidelines are not used.

Another example of what can be considered as questionable human performance studies is the type whose objective was to say something definitive about visual or televisual acquisition of targets. Many of these studies have made use of very simple, high-contrast symbols such as Landolt C rings as the stimulus material. Such stimuli are easy to use in a laboratory and easy to score, but until we convince the enemy to paint his equipment so that it has high contrast with the background, the relevancy of these data is highly questionable.

Studies on communications have studied the allowable signal-to-noise ratio, but all too frequently the only task an operator had was to listen for the signal. Our current standards are based on the results of these studies in which the operator was not "loaded" as we might expect an airborne operator to be. We have recently empirically demonstrated that a much higher signal-to-noise ratio is needed if the operator will be engaged in another task at the same time. The lack of validity of the earlier studies occurred because of a lack of consideration of how busy operators might be.

Human performance studies have been conducted in static-base simulators to determine the adequacy of new displays such as head-up displays and new controls such as side-arm controls for air combat maneuvering where a pilot is certain to be pulling five to seven g's. The lack of these highly relevant environmental variables must certainly affect human performance and the data from such studies may be totally invalid for the intended purpose.

The point of this discussion is merely to emphasize that too often in the past much time and effort and money have been wasted collecting the wrong or irrelevant data. Too little thought has gone into considering what the objectives are that we should really be addressing, what stimulus parameters should be included in the study, what methods should be employed to provide variation in the stimulus complex, and what criteria should be used for operator performance. We must have a more disciplined approach to planning human performance studies for airborne operators so that the data will be relevant, available, and in a form that is usable by the crew station design team.

METHODS OF DATA ANALYSIS

Another major pivotal issue in human performance studies is deciding what method to employ to analyze the data derived from human performance studies. The traditional approach has been either some simple descriptive statistics such as means and standard deviations or some tests of significance such as t-tests or F-tests. It must be obvious, however, that what we need to know is what the functional relationships are between the various stimulus variables and operator performance criteria. For this purpose, expanded use of multiple linear or non-linear regression seems indicated. With the former approach one could only say whether, for example, different levels of vibration or noise or illumination made a significant difference in operator performance. With the latter approach one may establish the functional equation which allows prediction of operator performance not only at levels used in the study, but also at levels not used in the study. The studies must include all the relevant variables so that the functional equations may take into account the simultaneous effect of potential or anticipated combinations of environmental and task variables. By developing these functional equations one may, by taking the first derivative of these equations, determine maxima or minima for these curves to determine optimal combinations of the many variables. This analytical approach is so immensely more powerful than the traditional one that studies in human performance for airborne applications should require its use.

These functional relationships to operator performance cannot be derived, of course, unless some variation in the relevant parameters is allowed during the study. The choice of how many levels of each relevant variable should be used and whether the relevant variables should be manipulated independently of each other is another major pivotal issue in human performance studies. The major determiner for these decisions will be the parameter's range of variation in the operational situation for which the results of the study are to be applied.

While it is possible to interpolate between "levels" used in a study and also to extrapolate beyond the upper and lower levels used in the experiment, the farther the "distance" from an actual point to the extrapolated or interpolated point, the less certain one can be of the accuracy of the estimated level. For this reason, it is probably always desirable to have either one level at the anticipated operational situation level, or at least one level slightly below and another level slightly above the anticipated operational situational level. Usually, three to five levels are quite adequate for

a majority of parameters. The choice of only two levels is very risky and should be used only for parameters that are believed to be relatively unimportant or for determining wether some parameter has any relationship to the criterion being investigated.

NECESSARY VARIATION OF RELEVANT PARAMETERS

Another pivotal issue in human performance studies is the choice of the desired method of providing parameter variation. With some parameters, especially ones which, in the real world, are confounded with other judged relevant parameters, it is often desirable to use selected recordings of the actual real world situations of interest. Such recordings, in the form of still pictures, motion pictures, video tape, audio recordings, or magnetic tape recordings obtained from a variety of other types of sensors can be used successfully for providing: background "real world" environments for the laboratory created situation, stimuli to be used as the task itself, and/or stimuli to be used as the "driving" functions for the aircraft system itself.

The use of naturally occurring stimuli has several advantages: high face validity, true validity to the extent that the recording and playback method has fidelity and the samples recorded are representative samples of the real world operational situations, and such stimuli may often be relatively easily and inexpensively obtained. There are also some disadvantages associated with playbacks of previously recorded real-world situations: they often do not integrate well with the rest of the generated laboratory situation (often yielding distractions like a foreign movie with dubbed English or yielding the impression that "something is not quite right"), they contain a confounding of the relevant parameters which makes it difficult to determine the relative effects of the parameters of interest, and it is often difficult or impossible to either define or obtain what constitutes a truly representative sample.

At times it is easier (though not necessarily better or more defensible) to independently generate known amounts of known types of stimulation and determine what effect changes in these levels of stimulation have on the operator's performance. As a general rule, the design and analysis is simpler for independently generated stimulation than for naturally occurring stimulation; however, it is less realistic and tends to make the laboratory situation less believable and less predictable to real-world situations.

A compromise between real-world naturally occurring stimuli and independently generated stimuli is some sort of real-world modeling. Real-world modeling recognizes the real world as a complex system in which alteration of the system to achieve desired change in one parameter can (and often does) result in simultaneous, often unwanted, changes in other parameters. The major advantages to real-world modeling are: the experimenter regains partial control of what is presented in the study, the presented stimulation is far more believable, and it has a greatly increased likelihood of generating results which will predict to the real world. Real-world models, whether physical ones such as model terrain or mathematical ones such as an aircraft's equations of motion or electronic ones such as simulated reflected radar or simulated sensed infrared, are often expensive and time consuming to construct.

The decisions regarding the use of recorded naturally occurring stimulation, real-world simulated stimulations, independently generated stimulation, or some combination of these are difficult ones to make. These decisions should not, however, be made solely on the basis of what is available, but instead on what is really necessary to meet the objectives.

Returning for a moment to our earlier discussion of functional relationships, human engineering standards could be developed based on desired human performance rather than on specific engineering recommendations for each relevant variable. With such equations, the crew station design team could see that there may be a variety of ways to manipulate the relevant parameters to yield an acceptable level of operator performance. For example, again in the area of legibility, it is known that character size, contrast, and illumination level all affect legibility. Other variables such as vibration, g-level, orientation of the information to be read also are known to affect legibility. The crew station design team needs to have an equation which indicates what level of human performance can be expected if various sizes and styles of characters are used under various levels of illumination with various background contrasts under anticipated vibration and g-levels. Only with the facility to rapidly determine the amount of degradation in operator performance that can be expected under alternative crew station design decisions can the design team intelligently contribute to engineering tradeoff decisions during the crew station design process.

THE NEED FOR MATHEMATICAL MODELS

Finally, such equations are mandatory if we are ever to successfully mathematically model complex human behavior so that ultimately, through the use of sophisticated computer simulation programs, we will be able to accurately predict the anticipated human performance on a complex airborne weapon system

without having to actually create dynamic mockups of a proposed system. Such an approach is a natural evolution in the history of human performance studies.

Originally it was felt that the only good data would be those collected on the real pilot in the real aircraft while it is engaged in combat with the intelligent adversary. But we have for years now used simulated targets to successfully represent the enemy on our operator's displays. We have built immensely expensive facilities to realistically simulate the outside-the-cockpit visual world of the pilot. Even more expensive facilities have been constructed to realistically generate vibration and g-forces he will experience in actual flight. We have, indeed, simulated almost everything but the operator. With the advent of the large-memory, high-speed, digital computer, we now foresee the possibility of ultimately simulating entire systems digitally, including the operators. When this is accomplished we will be able to predict anticipated operator performance and system effectiveness without having to go through the time consuming process of building dynamic mockups of the crew station. But this cannot be accomplished without knowing the functional relationships between man's performance and the host of variables that are included in crew station design decisions. These functional relationships can only be established by conducting realistic and relevant human performance studies.

CONCLUSIONS

In closing, it should be obvious that the objective of human performance studies is first and foremost to ensure that the operator's performance will be at required levels in the airborne crew station. He is placed in an aircraft because he has a crucial role to play in the system. His mission is to perform those functions that have been allocated to him. He is not placed there to check out the adequacy of the escape seat or as a fashion model for the latest life support equipment. He is not there as a guinea pig for the latest state of the art in display technology. Indeed all the various disciplines that are represented at this conference must keep in mind that good crew station design results only when required operator performance is assured. And good operator performance is too crucial to system effectiveness to be guessed at. It must be measured and analyzed and the effect on operator performance must always be a necessary determiner of all crew station design decisions.

DISCUSSION ABSTRACT

• *Mr. Jex, Systems Technology, Inc.:* There are two obvious problems with using multi-variate regression techniques for optimizing crew station designs. First, mapping out the multi-variate, non-linear functions that are needed will require so many experiments that you will run out of mega-bucks before you get all of them done. Second, even if you could complete all the required research, the equations that would result from this approach would be so horrendously complex that few crew station designers would even look at them. In the end, we may find that the most cost-effective approach consists of getting highly experienced people together during the preliminary design stage and having them make the necessary design decisions.

• *Mr. Farber, Ford Motor Co.:* Our experience with the F-111B simulator at Grumman showed that by the time the simulation studies were completed it was simply too late to incorporate any of the design changes suggested by the studies. In designing a crew station, performance must be evaluated within the specific operational context in which the new system will be used. Yet there is never time to do a study as part of the design process that is comprehensive enough to take these factors into account. I think this is the central issue, and I think suggesting highly sophisticated and inevitably extremely expensive human factors studies is just the kind of practical impossibility that makes experienced design engineers throw up their hands. I think that as the systems become increasingly complex, we will need to depend more on sophisticated experienced people who are willing to go out on a limb and make recommendations on the basis of their general knowledge of the human performance literature. I simply do not think that these problems can be solved as part of the design process.

• *CDR Wherry, Naval Air Development Center:* I agree that we must anticipate what the operational conditions are going to be for our future aircraft. But I do not see any way out of doing the necessary performance studies to collect the relevant data for use in the crew station design process. The existence of many relevant parameters just makes the task difficult, it does not make it impossible.

• *Mr. Hollander, Hollander Associates:*

In the early days of electronics, we collected data, plotted it, examined the nature of the functions, and derived general rules or principles to account for the functions. Together, these rules and principles provided the framework for an analytical model that enabled us to truly predict the optimal design in some cases. This work is not close to completion, but it shows that useful models can be developed. I support our speaker in his conviction that this kind of work must be done if we are ever going to design systems that even approach the optimal; and I believe it can be done.

• *CDR Wherry, Naval Air Development Center:* I also feel strongly that it can be done. I would like to point out that we have many expensive facilities around the country which can now collect these kinds of data. But how should we analyze the data to determine the underlying functional relationships? And then, how should we model it so that crew station designers can use the model to arrive at tradeoff values? I do not expect that ultimately we would present a single long equation to the crew station designer. Rather, we would probably provide him with a set of engineering design principles. We will establish which variables are really important, try out different combinations of variables in the sophisticated model, and come out with values for probable operator performance. We can also go back in and change some of these parameters and come out with predicted degradation in operator performance. This is really what I am advocating. In order to get this kind of tool--which I see as necessary for the crew station design process--we have to do these human performance studies where the relevant parameters are present, at least during the study.

• *Mr. Allen, Systems Technology, Inc.:* I think we can see a contrasting approach to design problems between the Apollo program and many DoD projects. The Apollo program was typified by expensive and very successful simulation. The missions were successful, the crews overcame several critical emergencies, and apparently the crew members felt that the simulations were adequate for the purposes they served. At one time, DoD used fly-offs to choose between competing systems. An approach adopted later consisted of investing large amounts of money for design and analysis during the early development phase of a system. We have come up with some less than adequate programs despite the large amount of money invested in design and analysis. Now, according to the previous Secretary of Defense, we may be going back to the approach of designing competing systems and then having fly-offs. I wondered how you feel about some of this past history and what implications it has for systems design.

• *CDR Wherry, Naval Air Development Center:* I think there is a fundamental and important difference between the Apollo program and the typical aircraft development program. In the Apollo program, the engineering technology lagged behind crew station design technology. A lot of time had to be spent in developing effective propulsion systems, launching systems, communication systems, and so on. This gave the crew station design people the time they needed to do their job. But when a developmental program for an aircraft is started, most of the basic engineering technology is available. Because it takes less time to slap an airplane together, people become intolerant of waiting on the crew station design. So the crew station designer seldom has sufficient time to do his job.

Useful human performance data were obtained from the Apollo dynamic mockups, but they had to build dynamic mockups to train the astronauts anyway. I am not against static or dynamic mockups for design purposes, but I am saying that the human performance data we need should be collected *before* mockups are fabricated--while there is still sufficient time to make any recommended alterations in crew station design suggested by the human performance data. We just have not done that in the past, but we should.

Regardless of past history, I do not think we have a good way of accommodating the problems of human performance in the crew station design process. I am saying we need to develop technology to do this sort of thing and I do not see any escape short of doing some performance studies to get the necessary data. I do not think the necessary data are just hidden in the literature somewhere. I think they have not yet been collected.

• *Dr. Pierson, University of Southern California:* I would like to caution you that no amount of mathematical sophistication or statistical manipulation is going to make unreliable data trustworthy or establish a truth in an empirical world. In any event, the design decisions arrived at analytically should be verified by inflight data.

• *CDR Wherry, Naval Air Development Center:* Let me take that point by point. First, I am not going to argue about the mathematical truth. Our strength is the strength of ten because our mathematics are pure, or something like that. And I would always agree that we need to validate performance data. Even after we have intricately designed the crew station, we cannot afford to say, "Okay guys, you fly it now," without having had any test and evaluation

flight. That is mandatory. However, I see test and evaluation as an iterative process that goes on throughout the design cycle, and my point would be that we need ways of testing and evaluating design concepts for crew stations even before we go into fabrication and dynamic mockup. I think we cannot do this without understanding what relationships exist between the various variables and human performance.

• *Mr. Mancinelli, Naval Air Development Center:* In the past it has been the practice of the human factors people to criticize the end product and tell the development engineer what he did wrong, which anybody can do after the fact. CDR Wherry has been one of the leaders in trying to establish the design criteria for the engineer before he designs his product. I think this is a very good point.

• *Mr. Hoerner, Naval Air Test Center:* I think there is a missing link in the test and evaluation cycle. I am talking about the use of a dedicated aircraft on which we can program the flying qualities or the display qualities of the vehicle that is coming down the line. This approach would provide data on a more timely basis than dynamic simulations and is less costly than the approach you are advocating.

• *CDR Wherry, Naval Air Development Center:* You are talking about the generic aircraft rather than the system-specific aircraft so that one can try out different design philosophies?

• *Mr. Hoerner, Naval Air Test Center:* Yes sir. We could take an individual piece of equipment and put it in the dedicated aircraft for its specific T&E. This could be done before the whole aircraft system is ready for T&E.

• *CDR Wherry, Naval Air Development Center:* I think that approach certainly should be advocated today because we cannot do it the other way. We do not understand the functional relationships well enough to mathematically model the problem right now. However, I believe that we *can* gain the necessary understanding; and if we do, the generic approach may no longer be necessary. I think the procedure you advocate on the generic type of aircraft--to test out concepts--is a good one. Although it is certainly a way to test out new technology, I am not sure that it will always give us the data we need in a timely fashion.

WORKSHOP PROCEEDINGS

CHAIRMAN: CDR ROBERT J. WHERRY
NAVAL AIR DEVELOPMENT CENTER

WORKSHOP DISCUSSANTS

MR. ALVAH C. BITTNER, Naval Missile Center
MRS. CAROL J. BURGE, Naval Weapons Center
LCDR PAUL R. CHATELIER, Naval Air Systems Command
LTC ROBERT A. CHUBBOY, Federal Aviation Administration
MR. LEO B. COLLINS, Systems Development Corp.
MR. CLARENCE A. FRY, Army Human Engineering Laboratory
DR. RICHARD F. GABRIEL, McDonnell-Douglas Corp.
DR. GLORIA L. GRACE, System Development Corp.
DR. RAYMOND S. HIRSCH, IBM Corp.
DR. FRANK M. HOLDEN, USAF Aerospace Medical Research Laboratory
MR. DIETER W. JAHNS, Forschungsinstitut fur Anthropotechnik
MR. HENRY R. JEX, Systems Technology, Inc.
DR. DANIEL B. JONES, Martin Marietta Corp.
DR. EDWARD R. JONES, McDonnell-Douglas Corp.
DR. KENT A. KIMBALL, Army Aeromedical Research Laboratory
MR. THOMAS J. KLEIN, Vought Aeronautics Company
MR. WARREN H. LOWDERMILK, NASA Lewis Research Center
MR. STEPHEN MORELAND, Army Aviation Systems Command
DR. WILLIAM R. PIERSON, University of Southern California
MR. ANTHONY S. SANTANELLI, Army Electronics Command
MR. GERALD STONE, McDonnell-Douglas Corp.
MR. ARTHUR W. VOGELEY, NASA Langley Research Center
MR. RICHARD M. WALCHLI, Naval Air Test Center
MR. JAMES W. WINGERT, Honeywell, Inc.
MR. WESLEY E. WOODSON, Man Factors, Inc.

ABSTRACTS OF WORKSHOP PAPERS

OPERATOR WORKLOAD: WHAT IS IT AND HOW SHOULD IT BE MEASURED?

Dieter W. Jahns
Forschungsinstitut fur Anthropotechnik

The term "operator workload" generally refers to an integrative concept for evaluating the effects on the human operator associated with the multiple stresses occurring within man-machine operating environments. Viewing the human operator's role in man-machine systems as that of an information transfer and transformation component, a case is made for considering workload as consisting of three functionally relatable aspects: input load, operator effort, and work result. Workload measuring techniques having their basis in time-and-motion analyses, information processing experiments, and direct physiological measurement of the operator state are briefly discussed. The initial conceptualizations of a long-range research program are indicated, where the objective is the systematic investigation of operator effort exerted relative to specifiable input loads and performance criteria.

FUNCTION INTERLACE MODIFICATIONS TO ANALYTIC WORKLOAD PREDICTION

James W. Wingert
Honeywell, Inc.

Analytic prediction of operator workload has been used to evaluate the result of allocating functions to human operators for a specific system concept. A common workload definition used is the ratio of time needed to perform all required tasks to the time available. This technique has proved useful in that system concepts which impose excessive workload demands on the operator can be abandoned early in the development cycle.

The usual techniques involve task analysis, with performance time prediction based on eye-movement data, information processing time data and time and motion data. The human is typically modeled as a single-channel device. The results are quite conservative if complex well-practiced tasks are involved. Function interlace provides a model which permits time-sharing of attention capacity to yield workload predictions more closely in agreement with simulation workload data. The theory is not as yet substantially developed, although some validating laboratory measurements have been made.

WORKSHOP HIGHLIGHTS

OPERATOR WORKLOAD

• *CDR Wherry, Naval Air Development Center:* We will now discuss your feelings about workload. Is it, in fact, the difficulty of the task that is being presented to the operator? Is it the internal state of the operator? Is it the performance measure of an operator? Does the concept of operator loading have utility for the function allocator? Should all performance measurement studies we do in the future have an index of operator workload that can be cataloged and used by the people responsible for function allocation? Does it have utility for the crew station designer? Does it have utility for people who do human factors research, but to no one else?

• *Mr. Vogeley, NASA Langley Research Center:* The following areas are particularly important in attemptint to project the characteristics of future aircraft: air traffic control, collision avoidance, four-dimensional RNAV systems, and automatic approach and landing systems. Consideration of developments in these areas has led us to conclude that many future aircraft will be equipped with automatic control systems. That is, automatic systems that will be capable of takeoff, cruise, and landing without pilot intervention. This conclusion leads to the question, what is the pilot's function going to be? So the problem we have been wrestling with at Langley is how to define the function of a pilot in an essentially automatic aircraft. Now, bringing the discussion to the topic of operator loading, we ask ourselves how do we measure operator loading in a system in which the operator is not physically doing anything? In a system where the pilot is physically manipulating the system, Hank Jex's method of measuring workload is very powerful. But this method does not appear to be useful in the type of system where a pilot is not manipulating anything.

About six years ago we concluded that the pilot's main activity will be visual scanning. We further concluded that if you can tell what the pilot is looking at when certain things happen, you may be able to get some idea about how he is monitoring, managing, and making decisions about the operation of the system. For this reason, we expended considerable effort in developing methods for obtaining real-time measures of where the pilot is looking. We wanted a measurement device that does not influence the pilot's normal behavior and provides for automatic processing of the measurement data. An RFP for such a device led to a contract with Honeywell who developed the Oculometer, a point of regard measurement device that is now well known. We feel the Oculometer is accurate and responsive enough to provide the type of measurement data that we need.

We plan to use the Oculometer in developing a workload measurement system that addresses itself to the monitoring of automatic systems. We plan to study pilots' performance while flying the type of missions that future aircraft are likely to have. The pilot will fly these missions with conceptual type "hard" displays. We will study the pilots' workload in that flight environment using Oculometers and control position recorders. We will place our major emphasis on studying the reception of information and the pilots' use of the information. We think this work is critical for understanding workload in future systems.

• *Mr. Moreland, Army Aviation Systems Command:* Previous studies with eye movement cameras have demonstrated that although you can determine what the individual is looking at, you cannot determine what he is perceiving. That is, you don't know whether the pilot is receiving the information from the display he is looking at or what he is doing with the information that he does receive.

• *Mr. Vogeley, NASA Langley Research Center:* I agree. That is one of the problems.

• *LTC Chubboy, Federal Aviation Administration:* Although we can measure performance in a variety of different ways, we do not yet know what these measures mean in terms of systems payoff. For example, we can seldom relate a given performance measure to safety. You can tell a program manager that a given display is going to lead to a certain amount of error and he usually says, "so what?" What does this mean for my system as a whole? Is it going to change the system's ability to perform its required mission? We also need to know what the pilot's capacity or reserve is.

A time-line analysis may indicate that the pilot is heavily loaded when in fact he is capable of handling this load with very little effort.

• *Dr. Pierson, University of Southern California:* I have a couple of points to make about operator workload. The only physiological measurement of workload that is really meaningful in the cockpit is heart rate. As a measure of stress, catecholamines secretions are probably the best. The other part is potential or capabilities of an operator. I do not think this question can be answered. Several studies with post-hypnotic suggestion have shown that a man that is normally capable of bench pressing a weight 20 times can lift the same weight more than 200 times under post-hypnotic suggestion. Thus, capacity appears to be a psychological rather than a physical end-point. Physical testing and stress testing has shown that no one ever comes near the physical end-point so I do not think we can really measure potential.

• *Mr. Jex, Systems Technology, Inc.:* But, for a working definition, can't we consider Olympian performance to represent reasonable bounds.

• *Dr. Pierson, University of Southern California:* I do not think so.

• *Mr. Moreland, Army Aviation Systems Command:* At a recent AGARD meeting, attended by representatives from a number of different countries, the issue of heart rate was beaten to death and they ended up concluding that it did not tell you much. That is, because of the extreme variability among individuals, the heart rate for a given individual doesn't tell you much about the workload of that individual. It may merely reflect a normally high or normally low heart rate for that individual.

• *Mr. Stone, McDonnell-Douglas Corp.:* Although we have been discussing workload, we have yet to come up with a good definition of what it is. I think we must come up with a universal definition of workload that will enable us to make measures that will be useful in the crew station design process.

• *Mr. Santanelli, Army Electronics Command:* To me, workload is the amount of effort expended in the performance of a task or tasks within certain established tolerances. How close the operator approaches the criteria could constitute a measure of workload. If fatigue could be measured, this could constitute a measure of workload over an extended amount of time, say 15 to 20 hours.

• *Mr. Vogeley, NASA Langley Research Center:* I would like to try a definition of workload. It seems to me that you have to design for optimum system performance under more or less routine conditions. This means to me that you cannot routinely work a man at his physical or mental limit. The maximum routine workload must be such that the pilot has the reserve capacity to handle any imaginable emergency. Thus, I think workload should be defined in terms of what is required to handle emergency situations.

• *Mrs. Burge, Naval Weapons Center:* I have been accustomed to thinking of operator workload for the purpose of answering questions such as, "Will the pilot be able to perform a given mission?" "Will adding a certain device to the system make the pilot more or less effective in performing his mission?" The basic problem is almost always, "Can the pilot do everything necessary in the time available?" The answer to this last question is certainly pertinent and useful to designers of aircraft weapon systems. Predicting the answer before the system is built is important, but the technique for doing so is by no means perfected. Measurement of the discrete tasks is fairly easy, the on-going tasks more difficult, and the mental tasks extremely difficult. In our work, time has nearly always been the critical variable. Physical or mental capability to do the job, given an unlimited amount of time is seldom a problem. Consequently, for aircraft systems, I think the time-motion type of analysis is the most useful type of measurement.

• *Dr. Grace, System Development Corp.:* I think we are hung up in thinking of workload within the context of perceptual-motor tasks. The psychomotor aspects of workload in the crew station of the future will undoubtedly diminish and a thinking component will become increasingly important. Therefore, the internal state of the man must enter into a proper formulation of the definition of workload. We must have the courage to tackle the subjective as well as the objective, and thus make use of a very valuable source of data--in addition to instrumenting the man, we must begin asking him also to describe what is happening. Techniques for quantifying verbal reports exist and are used in other types of scientific endeavor. These techniques should be applied in the study of workload as it applies to the crew station design problem.

• *Mr. Jahns, Forschungsinstitut fur Anthropotechnik:* I agree with Dr. Grace. We can specify input load in terms of objective output measures and we can relate these measures to performance in simulators and other environments. But what we should be talking about is the effort the operator must expend to make the transformation from input to output. This is a time-variant space, so you never have a constant effort from one moment to the next. Unless we can come to grips with that, I think we should stop talking about workload and fall back on the measurement of performance decrement.

• *LTC Chubboy, Federal Aviation Administration:* My problem is somewhat different in that I know what an acceptable workload level is. Pilots tell me that an instrument landing approach is an acceptable workload. My problem is defining a way to measure it. My approach is to measure pilot activities and, hopefully, some physiological parameters during the entire terminal-area operation. I plan to obtain measures in day-to-day operations over an extended period of time and obtain a statistical description of the subsets and elements of the task. I feel that this statistical description will define average workload for that task. My main problem is an acceptable physiological measure of workload. I feel that this physiological measure must be obtained for line pilots just as you in the military feel that physiological measures must be obtained from tactical operators. Unfortunately, the line pilot will not tolerate any type of encumbrance. So I hope I can find from this discussion if there is a package that can be installed in the cockpit that will provide the required physiological measures--if these are indeed meaningful--and still be acceptable to the line pilot. With this type of baseline data available, one can evaluate new equipment or procedures by comparing the workload for the new system with that for the old one.

• *Dr. Holden, USAF Aerospace Medical Research Laboratory:* The concept of workload that we designers must use is the amount of work expenditure required for the man to achieve acceptable performance. If you cannot define the criteria for acceptable performance, I do not think you are in a position to worry about workload.

• *Mr. Jex, Systems Technology, Inc.:* Even though we can define performance criteria in a broad way, there may be several response strategies that result in acceptable performance. It is only when workload approaches an absolute limit that there is a uniquely superior strategy. One idea that is being used in the control area is the notion of the meta-controller. You can do multi-channel things, such as rub your head and pat your stomach simultaneously, when you have practiced the task to a sub-delegated level. The thing that limits channel capacity is not the ability of the neuromuscular system to reproduce complex movements at a high information rate, but rather, limitations of the human in remembering the sequence of complex movements. This explains the pilot's ability to perform several simultaneous tasks with no apparent workload. Complexities arise when the pilot encounters novel situations or when he is required to learn new tasks. In these cases, the so called meta-controller channel is limited. For example, you can walk along the street and avoid potholes while buttoning your coat without even thinking about it, but you could not do this wearing a woman's coat with buttons on the opposite side. So workload must be defined in terms of the percentage of the operator's capacity, using a given strategy and assuming a given level of skill, for accomplishing a particular ensemble of tasks.

PRIORITIES FOR HUMAN PERFORMANCE DATA

• *CDR Wherry, Naval Air Development Center:* The question to be addressed in this session is as follows: "In light of anticipated technological advances, how would you propose to consider priorities for the collection of human performance data?"

• *Dr. Pierson, University of Southern California:* Statements of knowledgeable users of candidate systems, or similar systems, will point out the major problem areas. The priorities for research and development will fall out from surveys of these people. A secondary source is the design engineer. Where is he having trouble?

• *Dr. Holden, USAF Aerospace Medical Research Laboratory:* The traditional approach to the evaluation of equipment in the laboratory has been to measure the output from a control mechanism, to measure catecholamines and so on. However, it became apparent to us that there is not a direct transformation between the type of measures we were obtaining and the performance of the system into which the men and equipment would be placed. We now try to select performance measures that reflect what the operator is trying to accomplish, his mission. If the mission is bombing, we measure how effectively the system delivers the bombs. If the mission is electronic countermeasures, we measure effectiveness in terms of the change in aircraft attrition. So I propose, even with advanced systems, that changes in mission success be measured as a function of the design feature you are interested in. The use of less global performance measures might be useful in gaining insight into how the man is achieving certain levels of control, but they are not very useful in assessing changes in the total system. The issue is, how valuable is an understanding of what the human operator is doing for predicting ways to improve the performance of the total system? So I submit that to determine priorities for performance measures, one must first determine what the system is supposed to do and how system performance changes with changes in design.

• *Mr. Jex, Systems Technology, Inc.:* Are you proposing to use only system output measures? If so, supposing system performance remains invariant over the range of stressers used. In such cases you would obtain no useful information unless you obtain some type of human performance measure.

• *Dr. Holden, USAF Aerospace Medical Research Laboratory:* If I put a pilot's left hand in an icebucket and it falls off at the end of a mission, but he still gets his bombs on target, there is no decrement in performance at all, as far as I am concerned.

• *Dr. Pierson, University of Southern California:* What bothers me is that the reliability of the avionics is not any greater than that of the human. If you are using one as a constant and varying the other while using systems effectiveness as a criterion, you do not know whether systems error is resulting from the operator or the avionics.

• *Mr. Jex, Systems Technology, Inc.:* I would like to present a point of view that is different from Frank's. I think one should measure the operator's performance and total systems performance. Systems performance, by intent, is made insensitive to subsystem changes. That is what you strive for in a good design. A feedback system does this, the optimal system does this, and the human operator strives to do this. That is, he adopts strategies that maximize the homeostatic stability of the system. Hence, system performance is going to be insensitive to the applied stresser. An example is automatic landing systems which are shooting for an accident rate between one in a million and one in ten million. It would be impossible to conduct a simulation study in which you measured total system performance (safe landing vs. accident) that would reflect a doubling or tripling of the accident rate. It would simply take too long. But you can detect changes in crew systems design by taking inner loop measurements, measurements closer to the source of the problem. In fact, I think workload measures which try to maintain constant performance but measure the workload type effects are more sensitive than those that try to measure a performance decrement under a constant workload. Thus, I will put in a plea for inner-loop types of measurements while not ignoring the effects or connections with the total systems performance measure.

• *Mr. Bittner, Naval Missile Center:* I believe that before we can identify performance measures that are going to be useful in the future, we must take a long look at current technological advancements and predict what kinds of avionics systems we are likely to have in the future.

• *Mr. Vogeley, NASA Langley Research Center:* I would suggest that we work the problem backwards. If we can define the requirements, we have the technological capability to build automatic systems that will do a better job than man. However, even if we do have automatic systems we are not going to let the aircraft go out alone. So if we begin by assuming high precision automatic devices, we can ask ourselves what kinds of tasks the operator is going to have to do and, then, what types of performance measures we need.

• *LTC Chubboy, Federal Aviation Administration:* I believe you have to work forward. I think you have to know where you are today, in terms of workload and so on, before you can define where you want to go in the future.

• *Dr. Jones, McDonnell-Douglas Corp.:* I think that the first task we have to accomplish is to define what the technological advances are going to be, see how these are different from current systems, and start from that point.

• *Dr. Jones, Martin Marietta Corp.:* I agree, and this is the type of job that must be performed by someone at a very high level, such as ONR.

• *Mr. Wingert, Honeywell, Inc.:* It seems to me that as a first step we must collect performance data that are directed toward deciding what the role of the operator ought to be. Man has been an amplifier with auxiliary tasks to do for a long time. We must have human performance data to help us establish a reasonable basis for departing from this traditional role of the human operator. Once we have done this, I am willing to think about performance data that will help the designer optimize the system.

• *CDR Wherry, Naval Air Development Center:* I think we can conceive of the future pilot as having a role similar to that of the present backseat driver. That is, more of a decision maker, tactical coordinator, display monitor, sensor controller, and so on.

• *Mr. Stone, McDonnell-Douglas Corp.:* The assumption that the operator will sit back and take over when the equipment fails is a wasteful way to use man. We have to decide how to use man but in light of new developments and new requirements. The data we need are the data that will enable us to make this decision.

• *Mr. Moreland, Army Aviation Systems Command:* A good example of this is real-time image interpretation. We know that operators of future reconnaissance and surveillance aircraft will be required to make decisions in the aircraft that were previously made by ground based interpreters. So, it is obvious that we will need to do research on an operator's ability to interpret real-time sensory information with state-of-the-art sensors.

• *Dr. Pierson, University of Southern California:* I go along with the things that have been said but the systems we have in the field are not worth a darn. Should we be looking at advanced systems before we go back

and correct what we have now? You will never correct future problems if you don't know what the present problems are.

• *Dr. Holden, USAF Aerospace Medical Research Laboratory:* What is apparent is that we are all talking about data rather than theory. If we had a display theory that would determine what the man is capable of doing given the format of the display, you would not have a function allocation problem. You would be able to allocate functions in terms of cost. The problem is that the psychophysical research has not been oriented to developing theory that is applicable to the development of design criteria. Until we have more emphasis on theory we are not going to be able to look at advanced systems and evaluate them without a great deal of laboratory research. So I make a plea for the development of some more functionally oriented theory. If we cannot develop these theories, the only alternative method is to develop candidate systems and evaluate them in the laboratory. We can measure systems and subsystem effectiveness, but you cannot use these data in evaluating the next system that comes along.

• *Mr. Jex, Systems Technology, Inc.:* That has been the big problem with the past body of literature on displays and controls. The data consist of the ad hoc measurement of the difference between candidate systems and the resulting data cannot be extrapolated to new systems. The data have not been put into the context of a theory that can be modeled and extrapolated to a new situation.

• *Mr. Moreland, Army Aviation Systems Command:* Although I agree that theory is required for evaluating new systems concepts, we are faced with the immediate problem of assessing display concepts that are here today. For example, I need information today about how good a flight director system is.

• *Dr. Gabriel, McDonnell-Douglas Corp.:* It is not an either-or question. We have structural theories but we still go through structural tests. We have two functions to perform. One is to develop concepts and theories that we can use to predict what is going to happen and how we should design the next system. We also have a test function which is to perform the systems effectiveness tests to see whether indeed we are doing the job. So, there is no conflict. I agree, however, that in the past we have been devoting the majority of our effort to the test function.

• *Mr. Vogeley, NASA Langley Research Center:* Should we go on record as saying that we are not expending enough effort in theory development? If so, how should we get this work done? We are so busy putting out fires that we have no time left to devote to the development of a good theoretical foundation.

• *Mr. Bittner, Naval Missile Center:* It seems to me that human factors engineering has been suffering from this type of "comparative" research for 30 or 40 years. Although you can determine whether A is better than B, what happens when system C comes along? You must go back into the lab and evaluate C. This type of tail chasing solves an immediate problem but it does not solve long-term problems.

• *Mr. Stone, McDonnell-Douglas Corp.:* I agree that theory is needed, but I am concerned with the everyday working problems that I have. We have so many problems to solve that we simply do not have the time to develop theory. Have we not agreed that you have to handle both problems simultaneously? That is, solve your day to day problems and garner what information you can that would be relevant for theory development.

• *Mr. Jex, Systems Technology, Inc.:* The test people should be exposed to the latest theory that will guide them in what measurements to make. By the same token, the theory developers should take a closer look at existing literature in an attempt to find data that may enable theory building to be done without additional research.

• *Mr. Bittner, Naval Missile Center:* I submit that we must make a positive statement regarding the need for theory development so that it will be set up as a formal part of the budget. If we say that we will deal with current problems and develop theory at the same time, the theory development will go begging in terms of the expenditure of time and resources.

OPERATOR ERROR VERSUS DESIGN ERROR

• *Dr. Pierson, University of Southern California:* Systems effectiveness cannot be assessed without considering systems safety. Systems safety has not yet been discussed, yet 85 percent of the accidents involve personal error.

• *CDR Wherry, Naval Air Development Center:* To me there is no such "animal" as pilot error. We expect pilots to do things which they cannot do, we give them complex tasks without the information on which to base accurate decisions, and we fail to give them adequate controls to tell the rest of the system what their decision has been. Yet when pilots do not do what we want them to do, we classify it as pilot error. I think we have made a terrible blunder by classifying these errors as operator rather than design errors.

• *Dr. Pierson, University of Southern California:* I did not say pilot error, I said

personal error. I'm referring to personal error which goes all the way through the system, from a maintenance technician putting the wrong nut on a bolt up to and including what we generally refer to as pilot error.

• *CDR Wherry, Naval Air Development Center:* What I was going to suggest was the use of a human performance program in tracking down the things that have been designated as pilot error to try and get at what was the design error. To me, it is all design error.

HUMAN PERFORMANCE CRITERIA

• *Dr. Pierson, University of Southern California:* I think if we are going to talk about collecting, measuring, and analyzing human performance data, we've got to know what we do with accuracy data. A lot of the data we collect are in terms of accuracy.

• *Mr. Bittner, Naval Missile Center:* A number of years ago I worked with someone on a problem concerned with carrier landings. We were looking at position and attitude error down the glideslope. One of the biggest problems we had was coming up with a metric of what these errors amounted to in terms of cost. That is, in relating these measures with the probability of an accident or a hard landing. It was difficult to come up with a single metric which said this system was better than an alternate system. In looking at different display configurations we found that some configurations were good for minimizing one type of error, whereas, other configurations were best at minimizing another type of error. Furthermore, an individual had the capability of trading off different types of error. But you can't even train someone to make the proper tradeoff unless you have a criterion. Until someone comes up with a way of making a metric such as this, you're not going to be able to optimize systems we have already, let alone evaluate systems that are coming along in the future.

• *CDR Wherry, Naval Air Development Center:* We have had the example tossed out about landings. Various criteria have been used in studies of real-world and simulated landings. Examples of commonly used criteria include: whether the aircraft crashed, whether or not the aircraft hit the number three wire; whether the aircraft stayed in the flight path all the way down, and what the aircraft was doing as it came down the flight path. All of these things are systems criteria. They are not human performance criteria because there is a big machine between what the pilot is doing and what the aircraft is doing. I want to know how we get at the measurement of human performance, so that we can tell designers how systems requirements can best be met. I think there is a big difference between operator performance and system performance and that we tend to get the two confused.

• *Mr. Bittner, Naval Missile Center:* Instead of talking about criteria for human performance, how do you set up criteria for systems performance?

• *LTC Chubboy, Federal Aviation Administration:* You can easily define man-machine performance in terms of the profile you want to fly and you can analyze what improvements you wish to make in displays and controls in terms of that profile. I admit you have to look at a multitude of profiles, but there is no reason why the requirements should not specify the manner in which the machine is to perform that mission.

• *Dr. Holden, USAF Aerospace Medical Research Laboratory:* There is an interesting approach that is possible, although we don't yet know if it will work. If you know what the input-output behavior across the man is while he is performing his task, it is possible to postulate a set of criteria and determine what the man is optimizing. This can be done whether you're talking root-mean-square, time-on-target, or whatever. This enables us to determine what the man considers to be important instead of imposing artificial criteria on our experimental subjects.

• *Mr. Bittner, Naval Missile Center:* You said that we should let the man program himself and that you will merely tell him how well he is doing. But, before you can tell him how well he is doing, you must know what is better or worse than something else.

• *Dr. Holden, USAF Aerospace Medical Research Laboratory:* Well, hopefully, I know what the system is supposed to do.

• *CDR Wherry, Naval Air Development Center:* You don't feel any qualms about mixing up how well the system is doing and how well the man is doing?

• *Dr. Holden, USAF Aerospace Medical Research Laboratory:* I think they are so intimately tied together that to try to separate them is somewhat artificial.

• *Mr. Bittner, Naval Missile Center:* But, don't you find a good deal of variation from individual to individual in terms of how the operator attempts to optimize systems performance?

• *Dr. Holden, USAF Aerospace Medical Research Laboratory:* Let me give you an insight into what that variation can do for you. As you narrow down the criterion of the systems performance for any group of people,

their performance is going to become more similar. If the criterion is vague, like "a safe landing," one pilot may always stay slightly above the glideslope while another may stay right on the glideslope. If both pilots execute safe landings, you know those are not critical parameters to landing an aircraft. It's just the way those guys like to do it.

• *Mr. Jahns, Forschungsinstitut fur Anthropotechnik:* You can't measure total systems performance and then make recommendations about where in the system changes should be made when total systems performance is not meeting the desired criteria.

• *CDR Wherry, Naval Air Development Center:* If we measure only whether or not the system stayed in the flight path, this is the only question we can address ourselves to. That is, the system did not stay in the flight path. We do not know why. We do not know if it is a control problem, a crew station configuration problem, a display problem, or whether the man was simply too busy doing something else. I submit that we have to attack the problem of what we mean when we talk about the accuracy of human performance.

DATA REQUIREMENTS FOR TEST AND EVALUATION

• *CDR Wherry, Naval Air Development Center:* We have to certify weapons systems as being suitable for service use. The question is, what type of testing is necessary to determine whether or not the system is suitable.

• *Dr. Grace, System Development Corporation:* Current test and evaluation practice is limited in two ways. First, inadequate resources (both time and money) are typically available to accomplish a thorough research design in a representative operational setting. Second, variations in future usages of the equipment with respect to mission, operator characteristics, and potential retrofits are not adequately taken into account in the design of and accomplishment of test plans.

• *Mrs. Burge, Naval Weapons Center:* I am not sure what the official policy is, but I have observed many situations where systems were not tested with representative users and where the test conditions were grossly oversimplified. There should be stringent requirements for realistic tests of any system the guy in the fleet is going to have to use. Differences between the test situation and operational situation in which the system will be used should be described as part of the test report.

• *Dr. Pierson, University of Southern California:* The use of contractor furnished or customer furnished test pilots is an excellent way to test the functional limits of the weapon system. However, the operational pilot rarely operates at the limits of the system. Furthermore, experienced test pilots can often cope with system deficiencies that most operational pilots cannot overcome. What is a matter of pride to the test pilot often is a cause of injury to the operational pilot. Major problems with present-day test programs are: an insufficient amount of time is devoted to test and evaluation, and insufficient attention is devoted to operational maintenance.

• *Mr. Bittner, Naval Missile Center:* A lot of times, the reason that people who know a lot about experimental design do not make inputs into field testing is that they cannot design an experiment that is robust enough to survive the random influences of the test environment. A beautiful hierarchical design is of no value if one or two lost observations will devastate the design. I maintain that learning to design robust experiments is as important as randomization, replication, economy, symmetry, and the other classic criteria of a good experimental design.

• *CDR Wherry, Naval Air Development Center:* I would suggest that we don't have strong enough requirements for testing of systems under simulated operational conditions.

• *Dr. Holden, USAF Aerospace Medical Research Laboratory:* You mean that it is not built into the statement of work.

• *CDR Wherry, Naval Air Development Center:* I think there are some policy statements that say that the conditions under which you should do test and evaluation are to be as much like the operational conditions as feasible. When they say feasible, they include the money available to do the tests and there is never sufficient money available to conduct the tests. You cannot do them first, you have to wait until you have your pilots trained on what the mission is and how to use the equipment anyway. So they are the last thing you can possibly do anyway. I do not even know that things like tactical target flights necessarily result in changes to the system but they sure give you some insights into the problems that you have, including changes in tactics that you better introduce if you are really going to use that system.

• *Mr. Walchli, Naval Air Test Center:* Another important point concerns the representativeness of the system we are testing. In theory the test vehicle is supposed to be

representative of the vehicles that will be delivered and used in the fleet. In reality, I think there is often a big difference between the vehicle we are testing and the ones that go to the fleet.

• *Dr. Jones, Martin Marietta Corp.:* Sometimes the fact that the test vehicle is not like the one that will be used in the field is used as an excuse for not doing testing. Yet, if you look at them, there are a lot of things that are the same in both vehicles.

• *CDR Wherry, Naval Air Development Center:* I think what is being said is that testing is not a luxury, but a requirement. We have got to make people understand that it is a requirement to collect this type of data.

• *Dr. Holden, USAF Aerospace Medical Research Laboratory:* It seems to me that there should be a very good meld of three sorts of data: what happens in the field, what were the procedures and data collected during flight tests, and what happened during the simulations that were done on these systems. I know of no accurate correlation between the information gathered during the simulation and the information gathered during either test and evaluation or evaluation in the field.

• *Mr. Wingert, Honeywell, Inc.:* Acceptance test procedures can undoubtedly be defined which would markedly improve the present certification T&E. These would include larger test populations which more closely resemble the eventual user populations, larger and more sophisticated test courses which more closely resemble a stressed field environment, and more controlled experimental conditions. The greater emphasis on man-task measurements aside from the opinions of pilots can markedly improve the validity of these tests. We know how to do it better! A necessary first step is to convince management of the value of test and evaluation. Then we must be ready to define who is to be tested, what minimum level of simulation or flight test will provide valid results, and what parameters are to be measured.

SUBJECTIVE VERSUS OBJECTIVE DATA

• *CDR Wherry, Naval Air Development Center:* The next question I would like to throw out for discussion is the role of subjective versus objective data on human performance. What is its utility, credibility, and cost?

• *Mr. Bittner, Naval Missile Center:* There have been studies in which judges have been given measures and criteria. Then they were given a new situation in which they were given the measures and were asked to define the criteria. It was found that one of two things happened. It was found that people either tended to use a single metric or some non-optimal linear combination of metrics. I would suggest that since we are working with a multi-dimensional problem, subjective judgments have limited value.

• *Dr. Holden, USAF Aerospace Medical Research Laboratory:* Subjective observations are valuable for nailing down your hypothesis. I agree with Alvah that it is bad to use subjective data as the only justification for your final definition of a problem or your conclusion about how it should be solved.

• *LTC Chubboy, Federal Aviation Administration:* I would like to suggest that subjective data are good. One way you can improve the value of subjective data is to carefully define the descriptive terms, adjectives if you will, that are to be used in describing opinions and attitudes.

• *CDR Wherry, Naval Air Development Center:* I think you were saying that we should use a structured questionnaire instrument.

• *Mr. Fry, Army Human Engineering Laboratory:* A study is being conducted in our lab that is using the technique you described. They have developed a questionnaire which consists of antonyms with seven judgmental steps between them. I think this is a way of quantifying subjective data.

• *Mr. Moreland, Army Aviation Systems Command:* The Cooper rating is a way of quantifying subjective judgments.

• *Mr. Bittner, Naval Missile Center:* A local questionnaire study of helmets canvassed three sorts of people: the people who wore the helmet, acoustics people, and safety engineers. Each of these groups came up with reliable judgments as to what a good helmet is, but the helmets were altogether different.

• *Mr. Santanelli, Army Electronics Command:* In the types of studies we conduct we use both objective and subjective data. Sometimes, because something goes wrong in collecting the objective data, we are saved by the subjective data. So I think it is a good idea to always use both.

• *Mr. Jahns, Forschungsinstitut fur Anthropotechnik:* I think the emphasis in subjective measurement needs to be on getting clear-cut definitions of the verbal information that we are getting out of the subject. Once we have accomplished that we can make subjective data as reliable as objective data that we are currently getting.

• *CDR Wherry, Naval Air Development Center:* I wonder if subjective data should be considered to be performance data? Although it may be related to how performance went, I do not think it is performance data. I believe that unless you supplement subjective data you may be completely misled by it.

WORKSHOP SUMMARY

CDR Wherry, Naval Air Development Center: It is difficult if not impossible to try to summarize six hours of knock-down, drag-out discussions on issues on which we are not agreed in a few brief minutes. Our policy was to select items for discussion, discuss these items, and then have written comments. I have tried to summarize some of the comments, but we will go back through that with members of the guidance committee at a later date and perhaps come out with more cogent comments than I will give you here today.

We discussed several central issues in the area of human performance data requirements and measurement methods at out workshop. Because of the previously expressed wide interest in the concept of "operator loading" and the idea of "unburdening" the operators in airborne systems, we raised some questions: "What do we mean by operator loading?" "Does the concept have utility? And, if so, when?" And finally, "How should it be measured?" Dieter Jahns, Jim Wingert, and Henry Jex formally reported their thinking and some of the work that had been and was being accomplished in this area in our workshop. Judging from its written comments, the workshop was unable to agree on a definition of "operator loading." Basically, the group divided on whether operator loading should be defined as: 1) the sum of the task demands of the situation; 2) a felt internal state which is related somehow to a capability to perform; or 3) the amount of effort (physical, mental, and emotional) being expended by an operator. The recommended method of measuring "operator loading" differed depending on its definition. Some favored measuring physiological correlates and others favored determining how many additional task demands an operator could shoulder before performance breakdown.

The workshop participants differed widely as to the probable utility of "operator loading" for such crew station design decisions as number of crew members needed, allocation of functions to various crew members, and display evaluation. But we generally agreed that the concept of "operator loading" has utility to the extent that it can be quantified and is predictive of performance.

A second question discussed was: "What will be the role of man in future airborne systems, and how can we best determine the priorities for collecting needed operator performance data?"

In general, we felt that in future systems man will be more of a "system manager" and "decision maker," and less of a vehicle controller, although some aspects of all present tasks will probably be seen in future systems. The group listed several technological advances which will influence man's future role, including: 1) new display technology; 2) multi-purpose, flexible, reprogrammable computers; 3) speech recognition and synthesis by computers; and 4) increased automation, especially in vehicle control.

The workshop felt that we need to specify how man's role should change beforehand, rather than merely allowing his role to change by virtue of technological advances. We felt that the users of today's systems could be a rich source of information on this aspect of the problem, especially with regard to how we have not satisfied their problems in current vehicles.

While percentages differed among workshop members, we generally agreed that 20 to 50 percent of the budget for human performance studies should be dedicated to theory development such as how man handles cognitive functions, decision functions, and other mental tasks. The remainder of the budget might be dedicated to more applied performance studies directed at particular man-machine interface problems.

Some members pointed out that some part of the budget should be reserved for data exchange and methodology development.

A third topic discussed was the inadequacy of performance measures taken during the test and evaluation stages of system development. These inadequacies are best illustrated by unrealistic test situations in which pilots who are better and more experienced than the average user are used to evaluate the system. This problem is compounded because they fly in situations that are much less demanding than those that will be encountered in the fleet. The workshop feels that certification of aircraft weapon systems as suitable for service use on the basis of these unrealistic test conditions is extremely dangerous and should be discontinued.

Another topic discussed was the role of subjective, opinion-type data as opposed to performance data. We felt that subjective data was complementary but not a substitute for actual performance data. Many participants gave examples of erroneous decisions based on subjective data alone.

A rather lengthy discussion was held on what criteria are appropriate in studies that investigate human performance. Separating system performance criteria from operator performance criteria appears difficult, and members of the workshop requested addi-

tional time to consider this problem before submitting written comments.

The consensus of the participants was that the workshop had been both interesting and valuable, but that additional meetings would be needed to resolve basic issues and arrive at substantive, recommended solutions. Some suggested we form an inter-agency group to continue to meet and discuss the critical issues in human performance measurement and analysis and to better exchange ideas, methods, and results.

PRACTICAL APPLICATION OF HUMAN PERFORMANCE DATA

SECTION IV

DEVELOPMENT AND USE OF HUMAN PERFORMANCE DATA FOR DESIGN

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Abstract: *This paper describes the general requirements for developing human performance data for use by engineers in crew system design. It defines what human performance data should consist of and the design questions which it should answer. The basic requirement for development of a human performance data system is considered to be equation of behavioral with equipment parameters and derivation of equipment implications from such data. The paper concludes with a specification of the characteristics that an ideal human performance data system would possess.*

OVERVIEW AND BASIC ASSUMPTIONS

The principal point of this paper is that the development and use of human performance data (henceforth, *HPD*) requires more deliberate, sophisticated consideration than human factors specialists or behavioral scientists in general have applied. Most of us have the idea that data automatically fall out of an experiment. This is not really so. Licklider's (1960) distinction between data and information--"Information can be regarded as an answer to a question, whereas data are the raw materials from which information is extracted"--is pertinent here: what we need for design are answers to questions, and unless HPD are carefully mined and refined, we will not extract those answers.

I will begin with certain basic assumptions which, although they are directed at crew system design in particular, apply as much and more so to design generally. (This last may in fact be a sore point for crew system design engineers who prefer to think of their data problems as being distinct from those of other design engineers.) These assumptions are: (1) The primary purpose of HPD is to provide design information to the engineer, which does not, however, rule out other uses for the data. (2) The design engineer has special requirements for HPD that are not the same as those described by the pilot's informational and response needs in flying an aircraft, although the two are obviously related. (3) The basic problem in the development and application of HPD to design is the difficulty of equating behavioral with equipment parameters and drawing equipment implications from behavioral data. (4) Unless HPD are *organized* in terms of parameters and format into what can be called a data *system*, their utility is limited.

Without specifying it as a fifth assumption, we can probably all agree that there is currently a serious gap between the availability of behavioral data and the engineer's data requirements, both in terms of amount of data and--much more important--the ability to translate those data into design guidance.

The objection will be raised that all this is an old, old problem, and so what else is new? Human factors specialists tend to become bored with "old" problems; and therefore to disregard them. The only thing one can say is that to recognize a problem as being familiar does not, unfortunately, solve it. In fact, it is possible that the familiarity of a problem is in direct proportion to its severity.

This paper is not an exhaustive examination of what is known and not known about

[1]The opinions expressed in this paper are those of the author alone and do not necessarily represent those of the U. S. Army.

particular aspects of crew system design; one would need to write a book about that. The other papers at this meeting will undoubtedly enumerate some of the gaps that exist. Rather I have chosen to deal with the special demands imposed on HPD by the nature of the design process.

THE DEFINITION OF HPD

Everyone talks about HPD much as one talks about the weather, but with less clarity. It therefore becomes necessary to define what we mean, because that definition will, in part, determine whether or not we have a data problem and if so, what must be done about it.

Does HPD consist of:

- The raw quantitative results recorded at the conclusion of an experiment, without any design implications drawn from these?
- That material found in popular handbooks (e.g., Woodson and Conover, 1964) and military specifications like MIL-STD 1472 (Dept. of Defense, 1969)?
- Everything published in the open and closed (i.e., governmental) literature?
- Principles and generalizations resulting from reported studies?
- The human factors specialist's own analyses and expertise?
- All, some, or none of the above?

I prefer to define HPD as being: (1) a body of quantitative information which *integrates* the results of studies performed in various contexts and with different variables; (2) formally organized around both behavioral and equipment parameters which are related to each other by the structure of the data system (i.e., the questions which the data system is set up to answer); (3) phrased in performance terms; and (4) explicitly presenting the design implications of behavioral factors.

If one accepts this definition--and there will undoubtedly be those who quarrel with it on the basis of its being too severe--then presently available HPD are unsatisfactory. Raw results are obviously not integrated or organized, nor do they present design implications. Handbook/specification materials abstract only a small part of the data, and it is not easy to find many design implications in these guides. Everything in the literature, while available to the assiduous researcher, is definitely not integrated or organized. The principles and generalizations which comprise most of what is available to the engineer provide little or no specific design guidance. And the human factors specialist's expertise turns out upon examination to be largely "gut" feelings, significantly better than the engineer's own visceral analyses of the behavioral aspects of design, but hardly living up to scientific standards. Only one HPD definitional requirement is presently fulfilled, and then only partially: that is the requirement that the data be phrased in performance terms.

The most serious deficiency in what I think of as HPD is that it is not very design-relevant. True, its goal is design guidance. However, design-relevancy requires more than the general goal of using data in crew system development. It requires that the parameters which the data describe have *direct* implications for equipment design. Although some design implications can be deduced, these can be extracted only with difficulty. And in fact, most of the design guidance that is provided by human factors specialists consists of qualitative generalities. It may be said that the criterion of design relevancy imposes too severe a burden on the human factors specialist, that some room must be left for expertise and creative thought. However, that expertise is deficient unless it is based on meaningful data.

More pragmatically, one must consider the consequences of providing the design engineer with inadequate (as he sees them) inputs. Studies performed by my colleagues and myself (Meister and Farr, 1966, and Meister and Sullivan, 1967) have demonstrated quite unequivocably that if human factors inputs are not specifically and directly relevant to what the designer conceives of as his informational needs, he rejects them. He can do this because he is in control of the design process.

If HPD are to be utilized, therefore, they must be directly responsive to the kinds of questions the engineer will ask during design. These questions, with the kinds of HPD they demand, will be examined next.

ENGINEERING DESIGN HPD REQUIREMENTS

A distinction was drawn earlier between what the pilot needs to know and to do in order to fly adequately and what the engineer needs to know in order to design effectively. The former describes *what* the design will contain or present or permit; the latter *how* that design should be accomplished. The two may be easily confused because one must know *what* before one can deal with *how*. Obviously the engineer must know what the pilot must know and do in order to design these into his equipment; however, there are other things he must know as well.

If we look at the pilot's informational requirements (Cruise, 1964), we see that he must possess:

- Knowledge of external conditions, i.e.. nature of the terrain, geographic position of the aircraft relative to known points on that terrain and relative to other aircraft.

- Knowledge of how the aircraft is performing in relation to programmed requirements for aircraft performance. i.e., what is programmed for the aircraft and how the aircraft is performing relative to that program.

- Knowledge of changes in aircraft status as a function of time and in relation to the mission goal.

- Knowledge of how to produce required changes in aircraft status (e.g., how to climb, how to bank, etc.).

These familiar generalities must, of course, be translated into specifics pertinent to the particular aircraft being designed. They also impose needs for research data relative to the pilot's *capability* to perform the actions indicated by these knowledge requirements. Some examples of the research data needed, particularly as they relate to displayed information, are:

- How much of the information required is best sensed directly or by means of intervening displays or symbology?

- How much information can be assimilated and reacted to by the pilot in a given period of time?

- How rapidly can the pilot perceive and respond to that information?

- How many channels of information can be monitored simultaneously?

- How does pilot performance change as a function of time?

The pilot's information and response requirements therefore require a type of HPD (pilot capability data) which is critically important for the designer. This is the bridge between the pilot's information needs and the designer's needs. However, most of the engineer's needs for information are somewhat different.

PILOT CAPABILITY

The engineer needs to know first: what is the *minimum level of performance* that one can expect of the pilot for a mission to be accomplished?

Pilot capability information is needed for inclusion in the design specification, to serve as a standard against which the designer can evaluate his choice of design alternatives. We know from previous research (Meister, 1971) that the engineer refers constantly to his design specification as the criterion against which he selects certain equipment or equipment characteristics for his final design. For example, if fuel in a jet engine must be injected at no less than a specified speed, this speed determines the design of the engine intake valves, not directly of course, but as a criterion; valve designs injecting fuel at less than this speed will be rejected.

From a behavioral standpoint the system to be designed also makes certain performance demands on the pilot which must be within the pilot's capability and which in consequence impact on the design of the pilot station. If one knows what the minimum is that the pilot can do in response to a requirement, this sets a lower bound on what can be asked of him. For example, if a pilot can resolve visual stimuli accurately only if they are one minute of arc or larger, it is no good requiring him to resolve 20 seconds; for that matter it makes no sense to provide him with an optical probe that can resolve to a fineness of five seconds. It is necessary therefore to extract these behavioral performance demands and levy them as a minimal requirement in the design specification. This can be done only, however, if the HPD are available which indicate what the pilot is or is not capable of doing.

In the past, military design specifications have not included specific quantitative performance requirements levied on the pilot. Whereas it has been possible to specify detailed performance requirements for aircraft systems (e.g., speed 250 knots, range 500 miles, etc.), it has not been possible to specify pilot performance requirements (e.g., response time in T seconds, control accuracy to five feet, etc.). At the most, statements were included such as "equipment shall be designed such that pilot performance will be optimized." Such a standard obviously cannot be used as the basis for evaluation of design decisions.

One reason why more definitive pilot performance requirements have not been included in design specifications, other than the natural reluctance of equipment-minded engineers to consider behavioral factors, is that performance capability data which can be readily related to equipment parameters have not existed in any integrated fashion. Consequently, when it is necessary to develop a design specification for a new system, these performance aspects are often ignored. The lack of behavioral requirements in specifications means that the engineer tends not to consider pilot performance as a major factor

in setting up his design.

The reason for concentrating on the pilot's minimum performance capability--the least he must do to satisfy a requirement--is that the expense of developing equipment is so great that only that minimum design capability can be provided which will enable the pilot to perform to an operational requirement. Manifestly it is possible to develop instruments which can enhance the pilot's performance tremendously, but the cost of doing so is usually prohibitive. For example, it may be possible with a system like a Ferrand window to give a pilot more than 180 degrees field of view of the terrain, but if the pilot can function adequately with a 120 or 60 degree field of view, less sophisticated viewing systems can be used.

EQUIPMENT PARAMETERS

The second question the design engineer asks is: On the basis of pilot performance, what equipment parameters should be considered in arriving at a design solution? For example, in developing a display, only some of the parameters involved in that display--field of view, resolution, brightness, contrast, etc.--may be important, depending on their individual and interactive effects on pilot performance. From the engineer's standpoint, which of these parameters should receive most of his attention? The more parameters that must be optimized in designing a given system, the greater the difficulty of implementing the design and the greater its cost. Depending on the particular set of parameters emphasized, the resultant system design may vary widely.

Since the engineer must decide on the behavioral parameters to be considered in his design, it is apparent that one of the functions an effective HPD system should perform is the listing of equipment parameters relevant to a behavioral function and the class of equipment involving that function. However, it is not enough merely to list those parameters, they must also be weighed on some sort of scale of relative importance to pilot performance so the engineer can decide which he should emphasize. Ideally, such a scale would be based on the amount of variance which the parameter contributes to overall performance, but even a crude ordinal scale would be useful. It will be objected that any absolute set of weights is impossible, since the overall design context will modify the relative importance of the parameters. Even so, some scale for frequently encountered design situations, however gross, could be developed.

Unfortunately, few pilot performance parameters are listed in design specifications, although this is one question which behavioral research is most competent to answer. Behavioral research is geared to testing the significance of individual parameters; the introduction of more complex experimental designs, such as multivariate regression analysis, should make it possible to develop quantitative weights for interactive parameters.

EQUIPMENT CHARACTERISTICS

The next question to be answered by the design engineer is: What equipment configuration, for example a display involving a specific size of scope, field of view, amount of resolution, should be selected to satisfy a requirement? This is the essence of the designer's art. It is here that the human factors specialist hopes to make his most important input, in terms of suggesting that configuration most suitable in terms of his pilot performance data. Theoretically, if pilot performance is a response to a unique combination of equipment characteristics, then one could work backwards and, by specifying the desired pilot performance, suggest the most effective equipment.

Unfortunately, there is no unique design solution in the sense of a single combination of equipment characteristics that will best solve each performance problem; several alternatives may do, if not equally well, then at least sufficiently well to be considered as design candidates. The number of potential equipment configurations that could satisfy any individual performance requirement is, although not infinite, much larger than could be dealt with by behavioral research. As a consequence, it is impractical to think of testing every possible combination of equipment variables and then producing a catalogue of pilot performance/equipment values, from which one would select the one most desirable design solution.

Attempts have been made to develop HPD banks which list different values of individual parameters and the performance values, in probability terms, to be expected with these parameters (Munger, et al., 1962). These have not generally been successful except in terms of demonstrating the desirability of the concept; the number of equipment and behavior parameters and the degree of interaction among them is so large, a comprehensive data bank would require more testing than is likely to be accomplished. On the other hand, although it does not appear feasible to collect data on *every* equipment-behavior combination, perhaps one could do so for *limiting values*. These limiting values are all the points on the equipment continuum which produce practically and statistically significant differences in pilot performance, the most important of these limiting values being the minimum performance capabilities referred to previously.

Thus, although pilot performance might

not be able to specify the type of design to be selected, it might constrain that design by indicating certain minimum values of the major parameters that enter into the design. For example, any display design involving a combination of resolution and field of view might be adequate, as long as the final design involved a resolution and field of view adequate to the minimum requirements of the pilot and the aircraft.

CONFIGURATION COMPARISONS

A fourth question the engineer must answer is: As between two or more alternative crew station designs, each one of which appears to be a reasonable design candidate, which should be selected on the basis of the pilot performance expected with each? Ideally this question would be answered by testing each configuration and comparing the results, but the engineer usually cannot or does not wait until the equipment is produced, even in breadboard form, to perform these tests. At early stages of design, the designer will conceptualize several equipment alternatives for a given operational requirement, and will select one to develop in detail. In effect, he performs a conceptual test. The engineer makes his choice on the basis of a number of design parameters, one of which is--or should be--pilot performance.

In the absence of the opportunity to test experimentally, one should have the kind of historical performance data bank referred to previously. One could then examine the various design alternatives, match their characteristics against those described in the data bank, compare the pilot performance that should result from each design alternative and select the one that provides the best performance. This is the procedure typically used by reliability engineers in performing design comparisons on the basis of anticipated equipment reliability. However, it has already been pointed out that an HPD bank based on all possible combinations of equipment characteristics is impractical. Nevertheless, even if a full scale set of HPD predictive tables does not exist, if we had one that specified minimal limiting values, it would be helpful in eliminating obviously inadequate solutions.

USER SATISFACTION

Even after the engineer has selected a particular configuration of equipment characteristics, the design problem has not yet been completely solved. Before the equipment can be turned over to the user, it is necessary to answer the question: Does the equipment as designed satisfy the operational pilot requirement? Obviously, if it does not, the design must be modified. This question can be answered only by testing pilot performance with the prototype equipment configuration and comparing system performance with the pilot performance requirement. Such a test presents no significant difficulty for the human factors specialist, since the performance measurement methods required should be well within his repertoire.

In the absence of a specified pilot performance requirement, however, the test fails to answer the question, since a basis of comparison is lacking. We come full circle again to the original pilot performance requirement indicated in the design specification.

EQUATING EQUIPMENT AND BEHAVIOR PARAMETERS

We turn now to the basic problem in producing meaningful HPD: the equation of equipment, task, and environmental characteristics with the performance that results from the pilot's reaction to these characteristics. In this discussion we shall ignore all but the equipment parameters.

An equipment parameter is some characteristic which describes the equipment and influences the use it is put to and how well it performs. Examples of common equipment parameters or dimensions are shape, size, weight, power output, scope, and brightness. A behavior parameter is some characteristic of the human which determines his response to the equipment, environment, or task. Common examples are arm reach, visual acuity, and memory. Human performance in the man-machine context is the consequence of the interaction of the two types of parameters.

Obviously, to the extent that one can define an equipment parameter in terms of a specific pilot response, the task of designing for the pilot becomes much simpler than it would be otherwise. What makes the task of defining equipment in terms of pilot performance difficult is that the two parameters function in two distinctly different domains, one physical, the other behavioral. Moreover, both sets of parameters function over time, although the changes that occur over time to equipment are usually so slow that they can be ignored by all except the reliability expert. Not so with behavior parameters--or some of them--whose values may change radically as a function of learning or fatigue.

Despite the fact that the two types of parameters function in two separate domains, some behavior parameters, primarily those of a perceptual or motor type, can be closely related to equipment parameters. There is a parallel, for example, between the field of view of a visual display and the operator's field of view, such that a variation in one produces a specific change in the other. On the other hand, certain behavior parameters

(primarily those that do not vary *within* the individual, such as body size) are independent of equipment parameters in the sense that, within limits, variations in equipment configuration have no effect on the behavior parameter. Consequently, they can exercise only a limiting effect on equipment design. By that is meant simply that the behavior parameter affects equipment design only at certain critical values. So, if a control location is within the arm reach of the 95th percentile pilot, locating it closer to him will have no significant additional improving effect on performance. Independent behavior parameters serve merely to constrain the design of equipment in a binary manner. This makes it easier from a HPD standpoint, since such critical values are easier to specify. On the other hand, since the performance associated with these limiting parameters is of an all-or-none nature, they cannot be used to suggest design *variations*. Unfortunately, most of our analytic human engineering evaluation devices, such as checklists, are based on these independent behavior parameters. The only quantification one can achieve with such evaluation tools is to count the equipment aspects that fail to satisfy these critical values.

Where there is a close tie between the behavior and equipment parameters, the task of supplying useful HPD is paradoxically made more difficult, because any variation in an equipment characteristic may give rise to a different performance value, and the individual incremental changes may be important. On the other hand, assuming that one has these equipment-performance equivalents, it is possible to control design by selecting equipment characteristics in accordance with desired performance.

In general, perceptual/motor parameters have a more direct relationship with equipment than do cognitive parameters, because equipment is controlled directly by perceptual/motor mechanisms. With cognitive behavior parameters such as estimating, anticipating, or analyzing, required by such systems as displays for terrain avoidance, radar navigation, or flight direction, the performance relationship to equipment characteristics is much more tenuous and design implications are correspondingly more difficult to suggest.

I have emphasized the equation of equipment parameters with their performance consequences in this section of the paper because that equation is critical for the use of HPD in design. Unless HPD suggest or permit the inference of a concrete relationship between the two types of parameters, it is impossible to extract any meaningful design information from the data. Unfortunately, most compilations of available HPD, as illustrated in typical human factors handbooks, fail even to mention the design implications of those data.

The question that should intrigue us is: Why or rather, why not? Is it possible that we lack a fundamental understanding (a model, as it were) of the man/machine interface we take so glibly for granted? Is design so idiosyncratic that generalizations are impossible? This seems unreasonable, because a few generalizations are impossible? This seems unreasonable, because a few generalizations do exist, although these deal primarily with design for simple controls and displays, such as scales, meters, or knobs. Perhaps the difficulty is that one is rarely dealing with only a single equipment and single behavior parameter at a time. Typically, equipment is composed of several interactive dimensions. Any equipment/behavior relationship is complicated therefore by interactive effects which must be accounted for by a weighting mechanism such as that referred to earlier.

The HPD system must therefore contain not only single-variable relationships, such as the effect of scope size on reaction time, but just as, or even more important, multi-variable relationships, such as the effect of scope size on reaction time when resolution is varied. It is the parametric *interactions* that are important in human performance, rather than (to use statistical terminology) the main effects of variables, because often these main effects are predictable from common sense, whereas the interactions are much less predictable. It hardly needs saying that multi-variable relationships present a particularly difficult problem and, in fact, available HPD describe few such relationships, at least in quantitative terms. Multi-variable relationships are especially critical because the engineer is constantly trading off design parameters.

In the process of moving back and forth between equipment and behavior in design, we must also deal with *hierarchies*. Both equipment and behavior involve hierarchical relationships, and engineers and human factors specialists both experience difficulty with them. From a human performance standpoint, it is necessary to determine the behavioral level to be described in one's data, such as a gross or detailed function, a gross or detailed task, or an equipment attribute. Both behavioral parameters and performance measures will vary with the hierarchical level selected. In consequence, the HPD system should be formulated at several behavioral levels corresponding to various flight operation and equipment levels. This increases the difficulty of developing the data system because the linkages between different levels--both in a quantitative and a logical sense--may not be immediately apparent. Nevertheless, since the engineer designs at various levels of detail throughout development, he cannot make most effective use of data at one level only. Unfortunately, most of our HPD are applicable

only to very molecular equipment levels, such as individual controls and displays.

Another requirement of the HPD system is that its design implications be spelled out, even if only grossly, as part of the system. This may be relatively easy with single-variable relationships, but much more difficult with multi-variable relationships. This difficulty is the very reason we insist on the proviso. If it is hard for a human factors specialist to extract sense from an item of HPD, then how much more so for the non-specialist? Moreover, the need to derive explicit design significance from a data item will serve as a check on the meaningfulness of that item. If it is impossible to specify the design meaning of a datum, it is possible that the datum is in fact meaningless, at least from a design standpoint.

PERFORMANCE MEASURES

Performance, the primary dependent measure in our HPD system, implies some sort of behavioral operation. But performance phrased in what terms? Three types of quantitative measures are available: (1) probability of success in accomplishing a mission objective or, at a more detailed level, a task; (2) behavioral descriptors, represented by response time, reaction time, or accuracy measures; (3) static measures implying no behavioral operation, most commonly found with anthropometric or related data.

The measure one selects should be appropriate to the behavioral level one is describing. For mission-related behaviors involving an entire system or a major equipment, success probabilities are most appropriate, because the system is concerned only with mission accomplishment; for individual tasks, behavior-descriptive data are adequate, although ultimately such data must be related to system success or failure. The performance measure to be applied to individual equipment characteristics, such as the length of a joystick controller, is very obscure, because one does not *behave* toward individual equipment characteristics.

The problem of interrelating these disparate measures is a knotty one, if only because of the large number of possible measures; I once found at least 35 different measures utilized in a review of 140 performance reports (Meister and Mills, 1971). A common metric would be highly desirable, and the use of the probability density function for this purpose has been suggested.

It is ironic that although our design guidance to the engineer may be based on HPD, that guidance is often phrased in purely qualitative terms. We find it almost impossible to make statements like, "If you adopt principle X in your design, it will result in 83% improvement in reaction time and an increase of 12% in overall probability of task success."

Performance data are particularly necessary when one wishes to select among alternative design configurations. Two cockpit layouts may appear superficially to be equally satisfactory, and may indeed be satisfactory if only qualitative principles are applied, that is, the avoidance of common human engineering inadequacies. Are both layouts then equivalent in terms of the performance that can be expected of them?

Is it possible to develop design statements in HPD terms? Does it ask too much of the human factors specialist? If the answer is yes, then a major revision of our data gathering processes is necessary.

THE HPD SYSTEM

Everything that has been said so far leads us to a specification of what the desired HPD system should be. Note that what is described is an ideal; nothing like it exists as an organized entity.

The picture of what is available to the human factors specialists is rather bleak, as any thoughtful specialist will agree. We have some data on perceptual motor functions, but practically none on decision-making, cognitive ones, and very little on multivariate relationships. It is my feeling, however, that many of the elements of the data system exist in the general literature. The literature, however, has not been mined to extract the necessary data, to analyze it and to compile it in an organized fashion, despite an increasing number of handbooks.

The ideal HPD system would have the following characteristics: it would be quantitative, of course, and phrased in performance terms, although not necessarily in a common metric. The system would be hierarchical. That is, recognizing that both equipment configurations and behavioral parameters range from the simple and molecular to the molar and complex, the data would be organized in a comparable manner. As part of this hierarchical development, the system would contain both single-variable relationships and multivariable relationships. Where multi-variable relationships were involved, the relative weighting of each variable would be indicated.

Data would be organized in terms of *flight operations* (e.g., terrain avoidance) and the *tasks* involved in each operation (e.g., monitor radar display). With each such operation and task, the following would be associated:

- *Type of equipment* needed to implement the operation/task (e.g., CRT). HPD must be related to equipment classes because the design engineer typically starts his design by conceptualizing a generic type of equipment which might satisfy the design requirement.

- The *behavioral function(s)* involved in the operation/task. This information is needed because the behavior/equipment parameters that must be emphasized may vary as a function of the behavior required. For example, the performance one achieves with alphanumeric displays will vary according to whether the function required of the operator is counting, naming, updating, etc. The detail level of the behavioral function employed should correspond to the detail level of the flight operation/task.

- The *behavioral parameters* involved in the preceding equipment class and function, with weights for each.

- The *performance measure* employed in the data available for each of these categories.

- *Design implications* of each major datum.

One can conceptualize the resultant data system as a series of matrices or more desirably an operation/function tree, in which each tree limb would represent a (preferably graphic) equipment-performance relationship. The tree arrangement would tie the individual parametric relationship back to the higher order operation and function from which it derives. Obviously, the literature as it presently exists does not provide sufficient data to develop a full-grown tree. This should not, however, prevent individual limbs from being completed and would at least have the virtue of letting us know where new data must be secured. Such a data-tree need not be exhaustive, at least initially; where a particular equipment-performance relationship is nonsignificant, perhaps all that would be required would be that this fact be noted in the system. Having attempted to develop HPD banks, I am not unaware of the extent of the task required to complete such a data tree. The difficulty of the task can, of course, be used as an excuse for avoiding the necessity of developing such a data system; the only question is whether one considers the importance of developing an HPD system great enough to warrant the effort.

Paradoxically, the fewer data human factors specialists possess, the less critical their services become to the design engineer. An "expert" without usable data is selling only his opinions; and in the market place of competing experts, opinions are cheap. Will behavioral inputs to crew system design be more readily accepted by engineers when they are backed up by an HPD system? Here, despite the difficulties and the problems which this symposium abundantly illustrates, I remain optimistic.

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DISCUSSION ABSTRACT

• *Mr. Farr, General Dynamics/Convair:* I agree completely with your paper. Such an approach gets things rolling, and allows for necessary integration of data, while keeping the overall data requirements within reasonable bounds. How we might convince all of those people in the different services and industry that this is the necessary approach is beyond me, but we all are rather tired of those fragmented approaches to data systems and access methods.

• *Dr. Meister, Army Research Institute:* I will repeat what I have said a number of times: that it is necessary for the human factors community, in cooperation with designers and pilots, to decide what data are required, what data are presently available, how useful these data are as they relate to design, and what additional data areas must be investigated. The problem is that although our community ordinarily bewails the absence of data, we have not systematically applied ourselves to the data problem as an integral problem. Rather, we are aware of inadequacies in our individual focus of interest, such as lighting or anthropometry, but do not view these inadequacies in the light of a general problem.

• *Mr. Mancinelli, Naval Air Development Center:* Your paper is relevant to a recently approved advanced development objective to evaluate and, if necessary, redesign every piece of personal and protective equipment in the Navy's inventory. In this program we will compromise performance requirements for inflight acceptability when necessary, because a piece of protective equipment is worthless if the aircrewmen will not wear it. With this in mind, it becomes very important that we have a data bank on human performance inflight so that we know where we can trade off protective features for acceptability. If performance data are not available, we are going to have to make guesses as we have in the past.

• *Mr. Farber, Ford Motor Company:* You pointed out very well the importance of getting human performance data into the design process, but the same problems apply to data on material performance. In other words, getting data into the design process is a general problem, not unique to human performance data. However, it is much more difficult to collect relevant and meaningful human performance data than it is to collect material performance data. Collection is so difficult in many situations that the problem of getting the collected data into the design process almost pales by comparison. Most of us who have sought to answer a design-oriented question about human performance have been struck with the difficulty of conducting a relevant experiment.

• *Dr. Meister, Army Research Institute:* If you are suggesting that the difficulty of deriving design implications from human performance studies or the difficulty of conducting studies that do have design implications makes such studies impossible, I can't buy that. The problem is difficult, but it is not insuperable.

• *Mr. Farber, Ford Motor Company:* I am not suggesting that the problem is insuperable. What I am saying is that the problem of getting data on human performance is far more difficult than that of getting data on the performance of physical systems. Materials and hardware systems are much less labile than human beings, much less responsive to changes in conditions. The human performer is influenced by his environment to a far greater extent than most of the materials that you work with in the aerospace industry. My point is that it is often extremely difficult to ask relevant questions in a form that can be answered empirically. This is a universal problem in any field that requires human performance data.

• *Dr. Meister, Army Research Institute:* Well, as CDR Wherry pointed out, when an experimenter sets out to conduct a human performance study, he must consider his objectives very carefully in advance. I grant you the difficulty of the task of stating meaningful objectives and performing relevant studies. But I think human factors people have been blowing their horn for a long time about the difficulty of dealing with human beings. The difficulty of the task should not dissuade us from being concerned about getting design-relevant materials out of our studies. Otherwise such studies are worthless.

• *Mr. Jahns, Forschungsinstitut fur Anthropotechnik:* I think we have a problem in determining who is to make the decision on what the human performance data requirements of the design engineers are, when human factors people and design engineers do not communicate appropriately with each other.

• *Dr. Meister, Army Research Institute:* I cannot believe that it is impossible for human factors people and design engineers to communicate, despite differences in terminology and perhaps in conceptual structure. It might take considerable brute force, but if we locked up an equal number of engineers and human factors people in the same room, in much the same way that a pope is chosen, I feel certain some meaningful answers would

emerge. As to who would decide on what are the human performance data requirements, I believe that these data must first and foremost satisfy design requirements. Consequently, the ultimate decision would have to be that of the design engineer. These design data requirements would have to be examined by human factors people to see if they are meaningful in terms of behavioral variables, but design utility would be my ultimate referent.

• *Dr. McGrath, Anacapa Sciences, Inc.:* I was concerned that, in your talk, you did not mention the magnitude of individual differences among humans nor the major impact that training and learning can have on human performance. We cannot describe humans in terms of a characteristic person, because the differences between people and the potential changes in the performance of a single individual as a function of training are so great. In fact, individual differences in performance very often far exceed the differences that you can attribute to environmental variables or the equipment parameters that you have listed. I have two questions. First, how would you handle individual differences and the effects of training in your data bank? Second--a question to the design engineers--what level of training do you assume of the operator when you design a crew system?

• *Dr. Meister, Army Research Institute:* I fully recognize the significance of training and of individual differences. I am not suggesting that we are dealing here with the concept of standard man. I would assume that the performance data would include measures of variability and dispersion. As far as training is concerned, this would be one of the behavioral parameters listed in that particular category, and the performance data would include performance at different levels of training. However, I have heard a number of design engineers say that, in designing a system, they assume an operator who has been trained to a reasonable level of operational capability and therefore they need not be much concerned about the training aspect.

• *Dr. McGrath, Anacapa Sciences, Inc.:* My concern was not that data on individual differences or the effects of training would be difficult to incorporate into a human performance data bank, but that such data would need to be prominently displayed. I say this because I think engineers do not appreciate the magnitude of individual differences among humans. In some cases, system performance could be improved far more dramatically by selecting the right operators or by providing them with the right training than by improving the physical characteristics of the system.

• *Mr. Hollander, Hollander Associates:* Somehow we assume the human being is variable and anything that is physical is fixed. I assure you that electronic circuits and mechanical devices also vary. Many components are first manufactured and then selected by size and by value. Similarly, equipment performance changes with wear just as human performance changes with learning and fatigue. We have to deal with ranges of performance in both fields. So, all is not different between the human side and the material side of the design process. In fact, I think we must aim for data specifications formulated in such a way that it really makes no difference whether we are talking about materials or human beings.

• *Mr. Jex, Systems Technology, Inc.:* A data bank similar to the one you propose has been 80 percent completed over the last decade in a behavioral field allied to crew station design. That is, the field of aircraft handling qualities. The functional equations connecting the system design parameters with the performance parameters have been defined over the past 50 years and have been computerized in the last decade. Elaborate empirical data have been carefully gathered connecting these functional parameters with the ordinal acceptability criteria. Finally, a rather elaborate set of guidelines, in the form of MIL STD 8785 and its backup documents, exists which provides a designer with a ranking or hierarchy of criteria, priorities, and allowable decrements so that he can effect the tradeoffs between the desirable system, the practical system, and a system operating under degraded conditions. What you propose in fact can and should be done in the broader field of crew system design. It is an extremely difficult, time-consuming process in which a multi-disciplinary group has to work together. If you want to look to an archetypal, successful effort of this kind, look at the past history of the handling qualities field and how its data base is used today.

• *CAPT Metzler, USAF Life Support Systems:* In the current development of fighter aircraft, the test and evaluation are supposed to be accomplished prior to production and used as a basis for deciding whether the candidate aircraft provides the best interface to optimize the operator's performance. What means of comparison or evaluation is really available? Are we currently reduced to MIL STD 1472 and qualitative comments by pilots?

• *Dr. Meister, Army Research Institute:* As things presently stand, in most cases, we are indeed reduced to MIL STD 1472 and pilot qualitative comments. I would argue, however, that we need not accept these evaluational tools, which I consider inadequate.

There are mathematical modeling tools presently under development which could be used. I draw your attention to the Display Evaluative Index technique of Siegel, which appears to offer promise in being able to provide a means for comparing alternative display configurations. Wherry's modeling technique, although it has not yet been validated, offers a possibility of determining whether or not the pilot will be able to accomplish his task as a function of specific equipment layout parameters. Siegel's Monte Carlo modeling methodology also offers promise and has been used, I believe, in either F-14 or F-15 evaluations. I recently compiled a description of the various techniques in a report which is available from DDC (AD 734432). More work might be needed to fully develop these techniques, but at least they show the way.

• *Mr. Bruns, Naval Missile Center:* I suggest that the Department of Defense establish a permanent tri-services group of scientists who are specialists in various aspects of crew system design. The group should have the following objectives: 1) integrate published research on crew system design into meaningful design source documents; 2) identify basic and applied research that is needed to fill the gaps in design source documents; 3) fund the necessary research and use the results to update the design source documents; 4) obtain feedback from operational users of the systems to identify design deficiencies; 5) create and update military specifications and standards which relate to crew system design; and 6) provide consulting advice to aerospace design engineers.

• *Dr. Meister, Army Research Institute:* I can only agree with the points you cited. It is necessary to attack the problem systematically and in an organized fashion rather than in the present rather anarchic manner, in which design research problems are attacked individually by individual scientists, and only in terms of an effort limited to the individual study. Most research is a product of the individual scientist or project group, and it rarely extends to efforts to integrate data, make them available, or determine their design relevancy. This might be an appropriate effort for JANAIR to get behind; yet I must admit I am skeptical about such an effort being pursued.

• *LCOL Boren, USAF Aeronautical Systems Division:* It is acknowledged that we fail to incorporate known human factors into our systems as they are developed, primarily because of a prevailing hardware orientation. I think a high level office in the Department of Defense serving as a focal point for human factors matters might help incorporate human factors into the system. Perhaps we should consider means to establish an office that would provide such a needed top management contact.

• *Dr. Meister, Army Research Institute:* I would approve of any means which might help to introduce system and order into an anarchic situation. Human factors does not have representation at sufficiently high levels of DoD, but certainly needs it. As to how this might be accomplished, again I refer to JANAIR as a quasi-governmental committee and take the lead in trying to get something like this established.

While listening to some of the comments that have been made this afternoon, I get the feeling that there are two distinct currents of thought. One says that really the problem is insuperable because of the complexity of the human and his behavior. The other seems to say there is no problem at all, it has either been solved or is being solved. A useful product of this conference would be some consensus as to whether we do in fact have an effective data system and if we do not have one, what kind do we need?

WORKSHOP PROCEEDINGS

CHAIRMAN: DR. DAVID MEISTER, ARMY RESEARCH INSTITUTE FOR THE BEHAVIORAL AND SOCIAL SCIENCES

WORKSHOP DISCUSSANTS

MR. RICHARD W. ALLEN, Systems Technology, Inc.
MR. WILLIAM H. BROWN, JR., Kaman Aerospace Corp.
MR. RONALD A. BRUNS, Naval Missile Center
CAPT EDWARD J. BURKE, Air Line Pilots Assoc.
CDR H. J. M. CONNERY, Office of Chief of Naval Operations
MR. GEORGE L. CRAIG, Naval Weapons Center
MR. DONALD E. FARR, General Dynamics/Convair
MR. JAMES D. GILMOUR, The Boeing Company
MR. RICHARD H. KLEIN, Systems Technology, Inc.
CAPT THOMAS R. METZLER, USAF Life Support Systems
MR. JAMES R. MILLIGAN, North American Rockwell
MR. RICHARD W. MOSS, USAF Flight Dynamics Laboratory
DR. CLYDE R. REPLOGLE, USAF Aerospace Medical Research Laboratory
MR. DARWIN S. RICKETSON, Army Agency for Aviation Safety
CAPT DANA B. ROGERS, USAF Aerospace Medical Research Laboratory
CAPT JAMES F. SANFORD, III, USAF School of Aerospace Medicine
DR. HEINE SCHMIDTKE, Technical University of Munich
DR. RUSSELL L. SMITH, System Development Corp.
MR. UTE WOLFRUM, Technical University of Munich

ABSTRACTS OF WORKSHOP PAPERS

APPLICATION OF MANUAL CONTROL/DISPLAY THEORY TO THE DEVELOPMENT OF FLIGHT DIRECTOR SYSTEMS FOR STOL AIRCRAFT

Richard H. Klein
Systems Technology, Inc.

Warren F. Clement
Systems Technology, Inc.

Flight directors for conventional aircraft do not provide the pilot with adequate information to maintain satisfactory performance and control of a STOL aircraft during landing approach. Closed-loop pilot/flight-director/vehicle analyses point up the important vehicle factors and show how they influence a set of pilot-centered and guidance-and-control requirements. Typical vehicles include those that require both airspeed and flight path control as well as those that are speed stable and hence require only flight path control. In all cases, a direct lift capability utilized for glide path control is assumed to be the unique feature of the STOL aircraft. A two-axis longitudinal director system is then designed from the principles of manual control/display theory for application to an augmentor wing type STOL aircraft. Since the synthesis of a STOL lateral director system is similar to that of a CTOL system, only the necessary changes and manual control aspects are summarized. The paper concludes with moving-base simulation results which verify the design technique.

A STUDENT PILOT AUTOMATIC MONITORING SYSTEM

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North American Rockwell

In conceptualizing the Student Pilot Automatic Monitoring (SPAM) system, two key decisions were made. First, the system was not designed as a substitute for the human instructor pilot but as an aid to the instructor. Secondly, it was recognized that the system, if it was to be economically feasible, would be capable of scoring and grading only selected portions of the student pilot's overall flight performance. Based on these concepts, a series of studies was made of the methods to be used in developing the system and of the system hardware and software requirements. These studies have indicated that a practical, economical SPAM system can be developed. It has further been shown that implementation and integration of the SPAM system into undergraduate military pilot training will result in significant cost savings.

PRACTICAL PROBLEMS IN USING HUMAN OPERATOR PERFORMANCE DATA

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During the past two years, human performance has been investigated within two generic system contexts--manually controlled antiaircraft artillery against high performance aircraft and air-to-air combat in air superiority fighters. The broad objective of this research was to assess the effectiveness of proposed air weapon systems, combat strategies, and countermeasures techniques. In meeting these objectives, it was necessary to address many problems associated with the use of human operator performance data. This paper describes six problem areas considered relevant for this workshop: system versus operator effectiveness, performance feedback, attrition modeling, stress tolerance, human operator identification, and system simulation.

WORKSHOP HIGHLIGHTS

DATA SUFFICIENCY, USEFULNESS, ACCESSIBILITY, AND APPLICABILITY

• *Dr. Meister, Army Research Institute:* It has been stated that the one deficiency in human factors is a lack of appropriate data. Do you feel we have sufficient human performance data? Are the data useful? Are the data sufficiently applicable to present-day design problems?

• *Mr. Milligan, North American Rockwell:* We have a tremendous body of data in handbook form on simple tasks, we have quite a bit of data on some complex tasks, and we have a large body of data on unique tasks and systems. However, when we develop a *new* system and we put together several simple tasks, several complex tasks, and several new tasks, we do not have the data needed to enable us to predict the performance of the new system. I estimate that the data are sufficient to answer about 85 percent of the basic single-task questions and about 50 percent of the interactive performance questions that arise in designing a crew station. Simulations or other tests are often required to answer the latter type of question. We constantly need new human performance data when new technology or equipment are introduced into the crew station.

• *Mr. Gilmour, The Boeing Company:* I would like to suggest that data imply measurement and measurement implies a metric, and in many cases we are concerned with parameters or variables about which we know so little that we cannot define a metric. In some cases we cannot even define the parameters. In those cases we have nowhere near the data we need. Performance under stress is a good example. I do not know how to define stress, much less measure it. In general, I feel that far too few data are available that are valid and applicable to the solution of a current design problem. Furthermore, I feel the data are not sufficiently accessible, in a proper format, or adequately organized.

• *Mr. Brown, Kaman Aerospace Corp.:* I think we have two different classes of people present. I am a general practitioner, not a researcher. I have found, despite the ambiguity in many reports, that I can retrieve more data on any subject than I can possibly use. So I am saying many data exist and 95 percent of these data are adequate for the problems I encounter. Also, there is enough replication for a man to make a decision as to what report he has faith in.

• *Mr. Farr, General Dynamics/Convair:* I would like to present a different opinion. As another general practitioner, many problems that I encounter cannot be resolved with existing data. For example, I frequently collect quick-and-dirty data in such areas as operator workload.

• *Mr. Moss, USAF Flight Dynamics Laboratory:* Existing data are sufficient for dealing with some kinds of problems, but the data are difficult to find. Improved techniques are needed for data retreival. The data should be organized according to the engineering discipline requiring the information.

• *Mr. Allen, Systems Technology, Inc.:* As a researcher who is continually asking new questions, I would say we do not have a sufficient amount of human performance data. However, it is not a matter of merely generating enough data, but of generating the proper data so that we can understand the fundamental phenomena we deal with. My experience has shown that fewer data are required when you understand the basic phenomena.

• *Mr. Schmidtke, Technical University of Munich:* Although we have good data on several biological functions of man, we are seldom able to estimate how workload, stress, or fatigue will affect the operator's performance in a given system.

• *Mr. Bruns, Naval Missile Center:* If a problem has a lot of commonality with previous problem areas, the existing data will usually be adequate. However, the data are seldom adequate for dealing with new systems such as FLIR.

In many cases the general practitioner in human factors does not have the time and/or expertise to review and synthesize the relevant data. We should integrate this material into cogent textbook-type formats for a wide variety of specific areas such as HUD symbology.

• *CAPT. Sanford, USAF School of Aerospace Medicine:* We have sufficient data to answer

almost any specific question related to human factors in aviation. However, these data are not useful for answering system-related questions.

• *Dr. Smith, System Development Corp.:* The literature simply does not apply to many problems most of us continue to face. The literature is useful in offering suggestions, but it all too often does not provide a solid basis for design. Most of the data are based on single- or two-variable experiments. And we know that the effects of single-variable manipulations usually are not additive.

Many of the relevant data are probably not accessible enough. A great deal of data generated from current military-associated research are classified. And everyone knows that acquiring classified data can often be a monumental task.

OPINION DATA

• *CDR. Connery, Office of Chief of Naval Operations:* I think opinions are legitimate data. We have seen subsystems and components built more on opinion than on hard data, and more often than not, they work. The decision to buy a new system is based a great deal on opinion.

• *Dr. Meister, Army Research Institute:* Is it possible that some of us are more pragmatic than others and are therefore willing to accept a somewhat dirtier criterion for data? Others who are less pragmatic and more puristic refuse to accept anything except data at a high level of specificity and purity and are unwilling to rely on opinion data.

• *Mr. Ricketson, Army Agency for Aviation Safety:* Opinion data can be quantified and shown to be linear so far as prediction is concerned. Expert opinion is being quantified and used successfully in many areas of application at the present time.

• *Mr. Allen, Systems Technology, Inc.:* The human being can be an effect-measuring instrument. But you must go to the trouble to calibrate the human if you expect to get reliable data.

• *Mr. Milligan, North American Rockwell:* Opinion and interpretation are often confused. Often times a large number of people will conduct experiments on essentially the same issue and draw entirely different conclusions from the data. In fact, a large number of individuals who look at precisely the same data will interpret it differently and, therefore, draw quite different conclusions.

ADEQUACY OF DATA FORMAT

• *Dr. Meister, Army Research Institute:* Is there any format that is particularly useful to the crew station designer?

• *Mr. Milligan, North American Rockwell:* I think the problem is not so much putting the data in a useful format as making the data easily available to the designer and convincing him that it is a useful item for the design process. Perhaps one should even teach the design engineer how to apply the data specifically. A number of models are being developed today and I think a good engineer is capable of using or interpreting a model assuming that he knows it is available, thinks it is important, and knows how to manipulate it.

• *Mr. Brown, Kaman Aerospace Corp.:* If you give the average research paper to a crew station design engineer who is working over a drawing board against a rigid time schedule, the data in that research report are simply not going to get incorporated into the design. The engineer needs hard points. The human factors engineer's job is to define the specific design implications of his data.

• *Mr. Allen, Systems Technology, Inc.:* I think that is true when you are interfacing with the hardware design engineer. However, when you are working with the engineer who is defining the functional aspects of a large and complex system during the conceptual stage of the development cycle, you need to give the engineer more information about human behavior in general.

DESIGN IMPLICATIONS OF DATA

• *Dr. Meister, Army Research Institute:* Are the design implications of the data we have at the present time made explicit enough in the reference sources? That is, do human factors engineers and/or design engineers assess the design implications of existing human performance data?

• *Mr. Schmidtke, Technical University of Munich:* It seems to me that only a small proportion of existing human performance data are directly applicable in the design process. In most cases an interpretation by human factors specialists is needed. In my experience, however, the design engineer can easily use anthropometric data and data on human body strength. Data on motor performance, mental performance, vigilance, etc., are not usually in a format that the design engineer can easily interpret.

• *Dr. Smith, System Development Corp.:* I feel that most human factors specialists, and most psychologists in general, do not adequately interpret the design implications of research findings. This appears to be the result of not reading the research literature carefully enough rather than a lack of capability. I personally know of many design implications given in human factors manuals that are incorrect or highly misleading.

If it is true that human factors engineers--who are presumably trained to carefully evaluate experimental results--all too often misinterpret research findings, how can we expect design engineers to interpret the data correctly? Handbook writers and experimentalists should have a more thorough understanding of what they have accomplished and written. Design implications should never be presented without a description of the assumptions underlying them. And I think design engineers should also work closely with human factors specialists in interpreting data.

I feel the human factors engineer is capable of assessing the design implications of the majority of data. But the implciations may or may not be responsive to particular design questions. Also, it may be impossible to use design implications to specify quantitative functional relationships between design alternatives and the mission performance of the system.

• *Mr. Allen, Systems Technology, Inc.:* Most human factors engineers can interpret the design implications of some classes of data. For example, human factors engineers have little difficulty interpreting data on letter format, color coding, knob shapes, and illumination levels. The implications of some types of data can also be interpreted by design engineers who are suitably sensitized to human factors considerations. But, some data require additional analysis to assess the implications for a particular design application. I feel that such analyses exceed the technical qualifications of some human factors engineers and most design engineers.

NEED FOR RESEARCH COORDINATION

• *Mr. Bruns, Naval Missile Center:* I think we have spent a great deal of time talking about what is wrong but very little time in talking about what we should do to make it right. I would like to suggest that the Department of Defense establish a permanent tri-services group of scientists who are specialists in various aspects of crew system design. The group should have the following objectives: (1) to integrate published research into meaningful design source documents, (2) to identify the necessary basic and applied research to fill the gaps in these design source documents, (3) to fund the necessary research and use the results to update the design source documents, (4) to obtain feedback from operational users of the aircraft in order to identify design deficiencies, (5) to update the design standards and specifications that relate to crew systems design, and (6) to provide consulting advice to aerospace crew station design engineers.

• *Dr. Meister, Army Research Institute:* In one of the chapters of a book I published last year that dealt with the types of research programs I thought were necessary, I suggested something very similar to what Mr. Bruns has proposed. I suggested that the government establish a DoD level organization which would take all of the scientists presently working in the human factors area and put them under a single umbrella for the simple purpose of eliminating the tremendous amount of redundancy and waste presently occurring. I suspect the government ignored my suggestion because they realize how difficult, if not impossible, it would be to achieve. But I think it is obvious to anyone who does any government work at all that human factors research programs are badly integrated and chaotic.

• *Mr. Allen, Systems Technology, Inc.:* I think the FAA and NASA should be included as well.

• *Capt. Burke, Air Line Pilots Association:* I think you should state your position even more strongly so the whole world would hear.

• *Mr. Ricketson, Army Agency for Aviation Safety:* The possible downfall of what you propose is that if you established a committee of distinguished scientists, you would have to give them a good deal of power. Empowering such a group to stop certain programs or to initiate other programs would be extremely difficult.

• *Dr. Meister, Army Research Institute:* I have no real expectation that such an organization will be established, at least in the near future. And I do not think Mr. Bruns thinks so either.

• *Mr. Bruns, Naval Missile Center:* No, not unless someone very high in the government sees this as an opportunity to save a lot of money and believes he can put together the power structure needed to get the job done.

• *Mr. Milligan, North American Rockwell:* To be a devil's advocate, what about redundancy? Often, two opinions are better than one. When you combine everything so that you only hear one voice, you often do not hear the other side of the argument. So, although we may pay for lack of communication and redundancy in effort, it is possible that the

benefits derived from having an organization where opposing views can always be heard is cost effective.

• *Dr. Meister, Army Research Institute:* There are certain dangers inherent in any such proposed organization. A large organization such as this could develop factions within itself and therefore perpetuate the same difficulties that exist today. But I still think the goal that has been expressed here is fine.

• *Mr. Bruns, Naval Missile Center:* Although you only have one organization making decisions, it does not mean you always have to take a single approach to solving a problem. This group could well recognize that it would be beneficial to fund two competing groups who have different approaches to solving a problem. The current flyoff procurement method exemplifies this philosophy.

WORKSHOP SUMMARY

Dr. Meister, Army Research Institute: Our workshop centered around certain questions: do human factors specialists really have the data problem so many of us have maintained, or is it essentially a figment of our imagination? One of the first things that became apparent is that there does not seem to be any single homogeneous entity called human performance data. Despite the urging of the workshop moderator, on the first day we could not get the participants to define precisely what they meant by human performance data, possibly because of the idiosyncratic nature of their data needs. Many specialists regard human performance data as consisting of everything in the universe, including the specialists' own expertise. In their minds, such data include not only what can be called actualized data--that is data that are stored, recorded, or published--but also potential data waiting to be unearthed as a solution to a problem. Now, for this second type of data we have the problem of developing a collection method, and many of the human performance data deficiencies cited related to this type of data.

Four questions were posed the first day to the group of about 20. Do you feel that we have sufficient data? Are the data useful? Are the data sufficiently accessible? Are the data sufficiently applicable to present design problems? The participants wrote individual answers to these questions. Without going into percentages, two distinct opinions seemed to appear. One group felt that sufficient, even more than sufficient, applicable, accessible, usable data exist; the other, that they do not. Attempts to find some characteristic to distinguish the two groups were not overly successful. One possibility is that the data needs of the general practitioner were different from those of the researcher. This explanation does not satisfy me. The most tenable conclusion I could reach was that this wide difference meant that the respondents were using different criteria to assess the adequacy of data. For example, if a crew system design problem involves five variables, and available data deal only with two, then the available data are sufficient or insufficient depending on whether one is satisfied with two variables or not. If human performance data are needed to solve new or exotic problems at the edge of the technology as it were, then they are insufficient. If the problems are simpler and more prosaic, then the data are adequate. If general principles are acceptable as problem solutions, then our data are adequate, for more specific purposes they are less adequate. A good deal also appears to depend on just how demanding the engineer is as a consumer or a customer for the data. If he is willing to accept less precise data, then the data are available. Otherwise, they are not. It appears, therefore, that many different types of human performance data can serve various purposes, and whether or not the data are adequate depends on the specialist's needs and his personal criteria for assessing data adequacy.

This morning's meeting concentrated on questions about communicating data to the design engineer. Again we asked four questions. Can the human factors man interpret existing data in terms of design applications? Can the design engineer interpret those data in terms of design applications? Can the design engineer make use of data on his own? Should design implications be implicit or explicitly presented as part of the data? The general feeling was that human performance data are capable of being interpreted by the human factors engineers in terms of design applications but that it would be dangerous to allow the design engineer to make use of these data without the assistance of the human factors specialist. It may be that there is a little special pleading there related to the need for protecting one's job. It is also very pleasing to me to be able to report complete agreement that human performance data should contain supplementary information indicating, at least in a gross way, the design use that can or should be made of the data.

This summary may give you the impression that little or no consensus is possible. This would be an overstatement. One gets the impression that whether or not there is a sufficient amount of usable data, existing data are not as acceptable or as integrated as they should be. As a case in point, I asked this morning whether anybody knew of any single compendium of human factors data particularly directed at crew systems design. Nobody could bring to mind one at all. Getting around to recommendations, the problem of data accessibility and integration is something that JANAIR and other agencies that sponsor research could well focus on. Though it may be difficult to change the nature and amount of our data through research, it is less difficult to make existing data more accessible and certainly more integrated. Accessibility is a problem of information retrieval and presentation rather than data generation. Although integration requires some sort of a conceptual structure, I think it would not be impossible to develop such a

structure. I suspect also that the inadequacy of our data, if there *is* any, is in part the consequence of its relative lack of accessibility and its somewhat disorganized state.

To sum up, at least 50 percent of the behavioral science community, assuming that our little group was representative, has a problem with the adequacy, completeness, and availability of human performance data. Unfortunately, the difficulty of defining human performance data needs is so great that no fortuitously assembled group of specialists like us can readily grapple with the problem. Human factors specialists do not appear to be particularly well equipped to handle what is essentially an epistemological problem, especially when it does not have an immediate concrete hardware referent. I suppose that is what makes human factors specialists capable of working well with engineers. JANAIR could, however, very well expend some of its resources on having a small group of sophisticated specialists look more intensively at the question of human performance data under perhaps less frenetic circumstances. Such a group should, in particular, consider ways to integrate the data and make them more accessible.

CREW SYSTEM CONFIGURATION AND WORKPLACE ARRANGEMENT

SECTION V

ANTHROPOMETRY AND KINEMATICS IN CREW STATION DESIGN

MR. KENNETH W. KENNEDY
USAF AEROSPACE MEDICAL RESEARCH LABORATORY

Abstract: *Attention to the anthropometric and kinematic characteristics of the aircrew member is essential to good cockpit design. Today, applied anthropology is performed by a variety of specialists in many industrial plants as well as research installations. The design problems are many in which anthropometric and kinematic variability must be accommodated. Many are crucial to the safety of the pilot and to the success of the mission. However, not everyone believes that human factors specialists have a rightful place in the design sequence.*

The magnitude of the variability of body size and proportions among the national military populations of the world is startling to the designer. We find among all American military populations a similar but, of course, lesser variability. Yet, it is sufficiently large, and our systems sufficiently complex, so as to produce a difficult design situation. The condition of current anthropometric and kinematic data is reviewed. Insofar as concerns basic conventional anthropometry on our using military populations, there are ample current data. This, however, is a temporary condition. We find ourselves terribly short in functional anthropometric and kinematic data. This latter condition, it appears, was brought on by two developments: (1) the coming regular use of computers in cockpit design, and (2) the advent of very high performance/high g aircraft and their high acceleration cockpits.

INTRODUCTION

Attention to the anthropometric and kinematic characteristics of the aircrew member is essential to good cockpit design. That this is true has been stated by a number of writers over the past several years. However, it is seldom said so emphatically as in the October 1965 U. S. Army analysis of Soviet human factors engineering activities. This analysis concluded the following:

> "The Soviets hold that the first prerequisite for coordinating human factors with the technical specifications of machines is to determine complete quantitative data on human physiological variables and functional relations. Only then can conclusions be reached about the effectiveness of a given man-machine system. Such elements of anthropometric information as general human measurements, dimensions of body parts, body movements, speed of movement of body members, strength, and body weight are mandatory. Knowledge is also required of other human physical characteristics such as center of gravity in various postures, moments of inertia, and total body surface. On the basis of these data, the designers can plan machinery and equipment." (U. S. Army Materiel Command, 1965, p. 3).

Today, applied anthropology is performed not only by anthropologists, but by physiologists, psychologists, medical personnel, engineers, and others, in the manufacturing industries, military and civilian federal research establishments, as well as in the universities and commercial research companies. They are involved in even more areas of applied research than those listed in the quotation regarding the emphasis on human factors in the Soviet Union. In this paper, however, I will limit my concern to anthropometry and kinematics.

RELEVANCE TO CREW STATION DESIGN

What kinds of design problems require consideration of these characteristics of the using population? The following are specific, actual cases in which consideration of the anthropometric and kinematic variability of the using population was crucial to the safety of the pilot and to the success or failure of the weapon system.

- Modification of an aircraft designated for special missions resulted in pilot accommodation problems, i.e., limited head and leg room and interference between body parts and the control column. It was necessary to severely limit the size of pilots permitted to fly this aircraft.

- It has been found that as many as 25% of the navigator-bombardier trainees cannot adequately reach their ejection handle.

- Pilots were programmed to wear the A/P 22S-6 full pressure suit during special missions using one of our first-line fighter-bombers. No cockpit compatibility tests had ever been performed to evaluate the spatial integration of a pressure-suited pilot in this aircraft.

- The following is quoted from the results found in an investigation of injuries during ejection: "The data collected in this study show positive correlation with...reports of lower limb injuries [in this aircraft], i.e., the greater the buttock-to-knee lengths of the aviators, the greater the likelihood of lower limb injuries upon ejection. The significant number of injuries can be attributed to obstructions imposed in the egress envelope." (Gregoire, 1972, p. 8).

- Installation of a new seat in one aircraft caused severe aircrew-cockpit compatibility problems: circulatory constriction, control column interference, hazardous ejection, restricted vision, and rudder pedal inaccessibility. Anthropological investigation was integral to grounding these modified, special-mission aircraft.

In addition, such findings as some of those of Muchmore and Madden (1959) on the X-15 in which it was discovered that some of the larger pilots could not manipulate all flight and emergency escape controls with their suits pressurized; or those of Grumman on the F-111B in which it was found that the pilot and MCO could not reach important areas when "cinched-up" in the seat (Grumman Aircraft Engineering Corp., 1963). In a recent LTV evaluation of selected USAF aircraft (Atkins, McClung, & McClendon, 1969), several important cockpit geometric deficiencies were cited. With regard to one aircraft, the "control stick is located too far forward. [The pilot] must fully extend [his] arm and shoulder to attain normal control application" (Ibid, p. 19). In another aircraft the "5 percentile pilot with restraint locked cannot reach the sub-consoles, operate the emergency landing gear 'T' handle or emergency stores jettison handle and can barely reach the emergency salvo jettison switch." In the same aircraft, "access to controls and displays located in both consoles aft of seat reference point are extremely difficult, if not impossible to use during flight" and the "throttle is located too far forward making access difficult for the small pilot in afterburner range" (Ibid, pp. 19 and 20). Differences uncovered in this evaluation were not only the result of inadequate attention to body-size data and kinematics in the original design, but also during subsequent, retrofit with new or additional equipment.

Of those conclusions arrived at in the LTV evaluation, two are especially disturbing and, therefore, worth quoting: "Basic human engineering principles and good crew systems design practices are not being applied when equipment is installed in out-of-production aircraft." And, "Physical inspection of aircraft and the confirmation of crew system requirements such as geometry, vision, etc., is a very difficult and important task; however, there are no clear requirements for such confirmation nor do guidelines on equipment exist for this purpose." (Ibid, p. 105).

The list goes on and on. Not all are as serious as these, and some are concerned with anthropological matters such as human strength capability, restraint systems, and other areas of interest excluded from this paper.

Because we are frequently contacted regarding problems such as these, I was somewhat dismayed at the bitterness in the tone of a "Letter to the Editor" in the June 19, 1972 issue of *Aviation Week & Space Technology*.

A missive was received from Mr. Anthony Nollet, a former General Electric design-team leader, responsible along with people from Lockheed for designing the AH-56A swiveling gunner's station in the Cheyenne helicopter. In his letter, after a selection of derogatory remarks concerning GE and Lockheed, he says the following: "The solid-waste reclamation business certainly has its share of dreamers. But we are fortunate because we have few, if any, of the following types: human factors people, systems analysts, program offices, PERT specialists, PPBS folks,

value engineers, zero defects people or any of the other non-performers who have built themselves snug empires in government and the defense industry in the last decade." He goes on to say, "I am convinced that the proliferation of these 'soft' disciplines is primarily responsible for much of the mess in the Defense Department." Mr. Nollet, obviously, does not have a warm place next to his heart for the likes of "human factors people" as well as a great many others.

In the past when I have been asked to say a few words on occasions such as this, I have usually assumed that I have been among good friends and converts. In nearly all such occasions this has indeed been true. There have, however, been a smattering of instances in which this has not been the case, and after taking all kinds of things for granted, I have found myself in the midst of an argument that might have been prevented had I prepared my talk in the proper manner. Whereas, I have no serious objection to an occasional fracas, they can be rather bruising to one's ego and therefore, when one might be anticipated, appropriate preparations should be made. So, on the chance that there might be an unbeliever in the audience, I will now offer a little necessary background information.

INTERNATIONAL ANTHROPOMETRIC VARIABILITY

Most people have a general appreciation for the variability in body size among the populations of the world, but for one reason or another, have never examined it in detail. Unfortunately, anthropometric data on all using populations of the world are not available. Data on the populations of Central and South American and African nations are very difficult to find. In many cases essentially nothing is known. Data on the Near and Far Eastern populations are incomplete, with the exceptions of Iran, India, Korea, and Japan. Some Southeast Asian nations are well known, particularly Thailand and Vietnam. The Australian population is reasonably well studied. North American and European populations are quite well known, except for Mexico, Spain, Portugal, and some East and most Southeast European countries. Anthropometric data on Soviet populations are not readily available. Among those countries from which anthropometric data are available, it is the military populations that have been given the most attention and about which I shall be concerned in this paper. In general, the civilian populations have not been well studied.

What are the anthropometric differences among the military populations of the world? For design purposes, are the differences significant? To answer these questions, it is instructive to consider some differences between the various national military populations through the use of percentiles. Percentile values are very useful to the designer because along with the actual design values, he also obtains an indication of the percentage of the population represented by that value. The significance and usefulness of percentile data are as follows: a 50th percentile value indicates that 50% of the population are larger and 50% are smaller than that value for that particular dimension. In the case of the 5th percentile value, 95% of the population are larger and 5% are smaller. Conversely, in the case of the 95th percentile value, 5% are larger and 95% are smaller.

Figure 1 (from Kennedy, 1972) is a display of comparative percentile values for stature. Military populations of the United States (U. S. Air Force, unpublished-b), West Germany (German Air Force, unpublished), France (Laboratorie d'Anthropologie, 1965), Italy (Hertzbert et al., 1963), Japan (Oshima, 1965), Thailand (White, 1964a), and Vietnam (White, 1964b), were selected for illustration. The United States Air Force flying population is among the largest, anthropometrically, of the military populations of western nations. For the purpose of illustrating some of the anthropometric extremes encountered, this population was selected as that with which the others are compared and, therefore, a more complete list of percentiles is reported for it. These can be seen on the left side of the chart. The populations are arranged from left to right in descending order of their values for 50th percentile stature. Thailand and Vietnam have been selected to represent those nations wherein we find the smallest of the industrialized peoples. To make it a little easier to interpret this chart, the 5th and 95th percentiles for each population are connected with a solid line.

Comparisons between some of these populations are startling to the designer. For instance, if, on the basis of stature, we apply the 5th to 95th percentile design range for USAF pilots to an item of equipment in which stature is a critical dimension, we obtain a design range of 167.3 to 187.7 cm (65.9 to 73.9 inches), or 20.4 cm (8.0 inches). Without design changes, this would accommodate essentially the same percent (but not percentiles) of the Germans, but only the upper approximately 80% of the French, 65% of the Italians, 45% of the Japanese, 25% of the Thai, and only about the upper 10% of the Vietnamese.

Notice the position of the Japanese population. With respect to stature, this population falls between Italy and Thailand. Fiftieth percentile stature for the Japanese is significantly shorter than that of the Italians and taller than that of the Thai.

To emphasize the differences in the

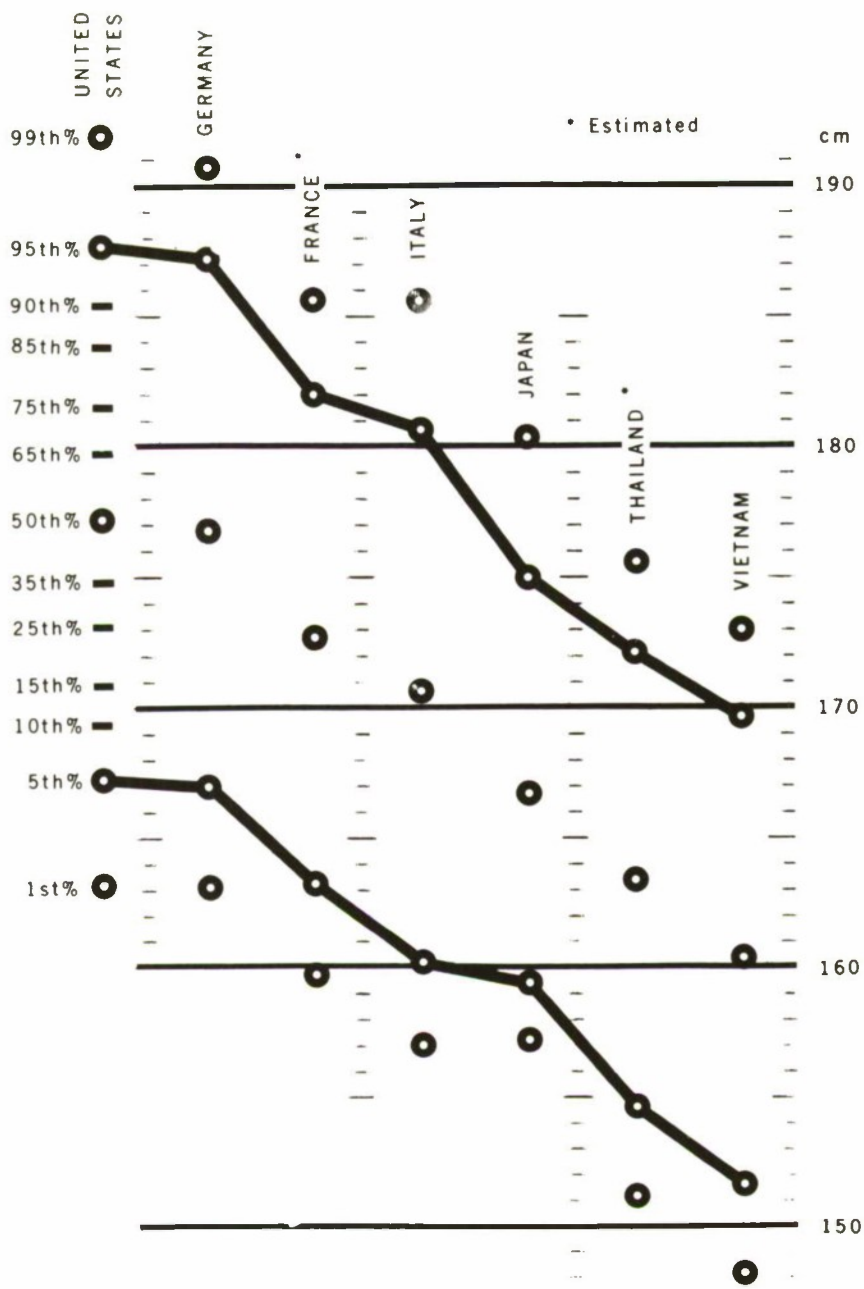

Figure 1. Comparative percentile values for stature: selected military populations.

sizes of the military populations of the world we can compare, for instance, both the Royal Thai Army and the Army of South Vietnam with the United States Air Force. Ninety-fifth percentile stature for the Thai is roughly equal to USAF 40th percentile; 95th Vietnamese stature is roughly equal to USAF 12th percentile.

Figure 2 (from Kennedy, 1972) presents a similar pattern of relationships for sitting height, which is a far more critical dimension in laying out the geometry of the aircraft cockpit, since it must be considered in determining the depth of the cockpit. We again see a relationship among the various populations similar to that we saw for stature. For sitting height, however, we find that the Japanese are slightly taller than the Italians and very nearly as tall as the French; for stature, the Japanese are significantly shorter than both the Italians and the French. Whereas most all other populations are more or less scale models of each other, the

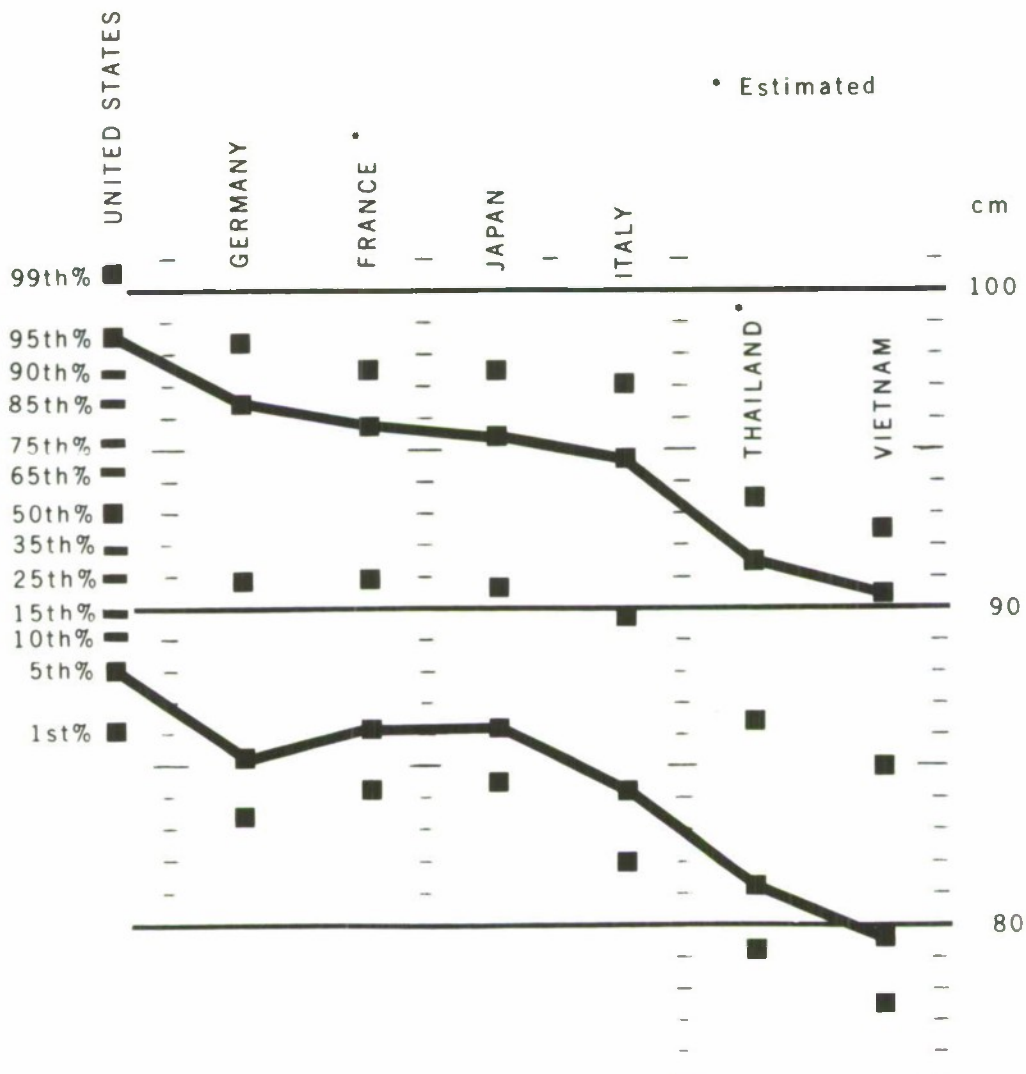

Figure 2. Comparative percentile values for sitting height: selected military populations.

Japanese are not, but rather are quite differently proportioned. Their torsos are proportionately longer than their legs, as compared with most other populations.

These combinations of big people, little people, relatively long and relatively short torsos, and short and long limbs have introduced into the design process a set of variables that is often the central issue in the success or failure of a man-machine system. This variability, not only in body size and proportions, but also in kinematics and muscle strength, is at the very heart of the anthropologist's armamentarium. It is in the application of his knowledge and appreciation of these ranges of variability that he has found his place in the crew system design process.

The Aeronautical Systems Division recently examined the possibility of designing an aircraft cockpit that could be compatible with the body-size requirements of both the USAF and the VAF flying populations. The problems encountered were phenomenal. It has proven at times quite difficult to accommodate to the extremes of smallness and largeness that we find in the USAF. To attempt to accommodate to yet another population, approximately 85% of whom are smaller than our 5th percentile stature, was found to be destructive to the entire design philosophy.

In most crew systems, the operator of average size is best accommodated. Those toward the extremes of smallness or largeness are invariably less well accommodated. In

crew stations such as the aircraft cockpit wherein body size has been found to be critical, it should be obvious that the range of body sizes adequately accommodated tends to be less than those systems in which consideration of body size is of less importance. To be more specific, in the aircraft cockpit, satisfactory accommodation for the 5th to 95th (or 3rd to 98th) percentiles in some critical dimensions may be all that we can expect. In the case of sitting height, this includes a range of four to five inches. Therefore, attempts to design for two such diverse populations as the USAF and VAF may not necessarily expect to accommodate above the 60th percentile for sitting height and other highly correlated dimensions in the USAF or below the 40th percentile among the VAF. We may not be able to accommodate more than 60% of each population.

We find among all populations this very same kind of variability in body size and proportion. Although in our military populations it is on a smaller scale, it is sufficiently large, and our systems sufficiently complex, as to produce a design situation in which there is, in addition to many other pressures, the requirement to take into consideration body-size, proportion, and kinematic variability.

ANTHROPOMETRY OF AMERICAN MILITARY POPULATIONS

What is the condition of anthropometric data on the American military populations? Anthropometric data on various populations within the U. S. Army have been reported by several investigators (Davenport & Love, 1921; Randall et al., 1946; Newman & White, 1951; White, 1961). The most recent being *The Body Size of Soldiers--U. S. Army Anthropometry--1966* (White & Churchill, 1971). *Anthropometry of U. S. Army Aviators--1970* (Churchill et al., 1971) is another. In *Body Size of Soldiers...*, 70 dimensions were measured on as many as 6,682 Army personnel from 18 branches of the Army, the greatest number (4,166) coming from the Infantry. In *Anthropometry of U. S. Army Aviators--1970*, 86 dimensions were measured on 1,482 personnel of all ranks from Private to Lieutenant Colonel, and classified variously as aviators, trainees, gunners, instructors, and other support personnel such as mechanics, machinists, and crew chiefs. Altogether, approximately 1,097 pilots and future pilots were measured. All subjects were stationed at Fort Rucker.

The most recent anthropometric data on Naval personnel can be found in *Anthropometry of Naval Aviators--1964* (Gifford, Provost, & Lazo, 1965). This is a report of 96 dimensions, measured on 1,549 U. S. Navy and Marine Corps aviation personnel, including aviation observers, pilots, flight surgeons, bombardier-navigators, and radar observers. Both officers and enlisted personnel were measured. Moroney (1971) recently reported selected bivariate distributions based on the 1964 Navy report. Altogether, 21 bivariates are presented in various combinations of 10 dimensions of importance in crew station layout. Moroney and his co-workers also reported data on five workspace dimensions, plus weight, percent body fat, and lean body weight, measured on 6,534 student Naval aviators and student flight officers (Moroney et al., 1971). The workspace dimensions were measured on an "integrated anthropometric measuring device." As yet unpublished anthropometric data were gathered in 1966 by White on U. S. Navy recruits and on Marines. The Navy recruit sample (White, unpublished-a) consisted of 4,095 personnel at Great Lakes, on which about 70 dimensions were measured. The same dimensions were measured on the Marine Corps sample (White, unpublished-b) which numbered 2,008.

The most fully published body-size data on the U. S. Air Force males is *Anthropometry of Flying Personnel--1950* (Hertzberg, Daniels, & Churchill, 1954). In this survey, 132 dimensions were measured on as many as 4,063 flying personnel, of several classifications, with ranks from Private to Colonel. Multi-engine pilots and navigators numbered a little more than half the total sample. Additional surveys of Air Force personnel were conducted in 1965 and 1967. The 1965 survey (United States Air Force, unpublished-b), Air Force anthropologists visited 17 Air Force bases to take 184 dimensions on a sample of 2,420 flying officers. An attempt was made to obtain a representative sample from each of the major commands. The 1965 survey data have not been published, though extensive data on basic trainees, about 70% of the sample, have been used for sizing clothing. The more significant data from the 1967 survey have been integrated into the various design handbooks.

In addition to these large-scale, general surveys, there have been several smaller, limited, specialized surveys. Garrett, in 1968, measured and reported a series of clearance and performance dimensions on the hand and, in 1970, reported an exhaustive series of 56 hand dimensions measured on 148 Air Force men. Alexander and Laubach, in 1968, reported data on a series of special dimensions of the ear. The American astronauts were measured on several occasions over the years since 1960 and reported in the NASA *Handbook of Human Engineering Design Data for Reduced Gravity Conditions* (Morton, 1971).

Equivalent anthropometric data on female military populations have been maintained over the years beginning, in recent times, with WASPs (Randall et al., 1946) and later on WACs (Randall & Monro, 1949). Data on WAF basic

trainees have also been reported (Daniels, Meyers, & Worall, 1953). Data gathered on a survey of Air Force females' hands (Garrett, 1970b) in which 47 hand dimensions were measured on 211 subjects are also available. The results of a 1968 survey of Air Force women have also been published (Clauser et al., 1972). In this report, data on 137 dimensions are reported on a sample of 1,905 female personnel, including 548 officers or officer-trainees and 1,357 enlisted women, mostly at Lackland and Sheppard Air Force bases.

FUNCTIONAL ANTHROPOMETRY

In recent years, anthropologists (and those who practice anthropology) have attracted significant criticism primarily for their alleged preoccupation with dimensions that have little applicability to design problems. This criticism has originated outside as well as from within their ranks. Several writers (Morant, 1947a, b; Morant & Ruffell Smith, 1947; Kind, Morrow, & Vollmer, 1947) recognized as early as 1947 that more functional anthropometry was needed in the design of crew stations. Dempster (1955a) stated that the applicability of conventional anthropometric dimensions is "limited to the same conditions that applied when the measurements were taken. That is, the measurements are not functional." This admonishment appears to have gone unheeded, since we find, for example, attempts to describe functional eye height in the aircraft cockpit in terms of the dimension, eye height--sitting, measured using largely artificial body attitude. A number of other researchers have also recognized the need for a functional anthropometry (Stewart, 1955; Roebuck, 1956, 1960, 1966; Chaffee, 1960a, b, 1961a, b; Rowland, 1960; Hertzberg, 1961; Kennedy & Clauser, 1963; Morrison, 1965).

Chaffee, in 1960 and 1961, forcefully but perhaps unfairly criticized the relative paucity of functional or dynamic anthropometry when, with regard to the 1950 Air Force survey report, he said, "To the crew station designer, it stands as a compendium of lengths, breadths, depths, heights, and circumferences, each virtually devoid of any apparent functional relationships to the rest or to any consistent unifying spatial reference system." So as to spread the criticism around a bit, he went on to say, "It must be mentioned here that the Army counterpart to the Air Force 1950 survey follows precisely the same regime and thus possesses identical shortcomings" (Chaffee, 1960a, pp. 17-18). I am sure he sould have said the same about the Navy's 1964 survey report, as well as most others since the date of his statement.

I believe this to be a fair judgment unfairly stated. In the 1950 USAF survey, at least 30 dimensions, almost one-fourth of the total series, were considered new. Most of these new dimensions were specifically created to be applied to several areas, crew stations being only one. Many of these dimensions have been noted by other anthropologists and included in nearly all major surveys since then. All dimensions have seen application in a number of other areas of research and engineering in addition to crew station design, and are still being used. They will undoubtedly continue to be used. Finally, except for the simplest dimensions, functional anthropometry simply does not lend itself to large scale surveys.

It is true, of course, that there are a number of design situations in which the traditional anthropometric data such as I have so far discussed, are of only limited usefulness. In the past several years a number of efforts have been initiated specifically for the purpose of making available to the aircraft cockpit designer a body of data more directly applicable to his needs. Some of these consist of conventional and new measurements taken over typical personal-protective equipment, with the subject posed in a functional body position. Others are measures of man's dynamic anthropometric characteristics. In the latter we see a merger of conventional anthropometry with kinematics, the study of movement. The literature, unfortunately, consists primarily of military and industrial technical reports, which, as we all know, do not see very wide distribution.

Hertzberg, Emanuel, and Alexander, in 1956, reported a series of functional body clearance dimensions for standing, crawling, kneeling, and prone body attitudes. Alexander and Clauser (1965) continued this series nine years later to include several dimensions on various other body attitudes.

Dusek (1958) reported information on the encumbrances offered by Arctic clothing. Chaffee, in a series of Convair reports, presented the first three-dimensional anthropometry--or andrometry--specifically applied to crew stations (Chaffee, 1960a, 1961a, b). In his 1960 report on anthropometry in the design of escape capsules, he presented three-dimensional data on 16 important body clearance landmarks. He also established the position of the mean "normal" eye of the human operator (at 31.9 inches above and 3.2 inches forward of the Seat Reference Point for a 15° back angle and 5° seat pan angle). Alexander, Garrett, and Flannery (1969) reported on a series of anthropometric dimensions measured on subjects wearing vented and then pressurized full pressure suits. Subjects were posed in typical crew station body attitudes.

INTEGRATION OF ANTHROPOMETRIC AND KINEMATIC DATA

The earliest that we find an integrated anthropometric and kinematic study specifically oriented to crew station requirements is Dempster's (1955) AMRL classic, *Space Requirements of the Seated Operator*. The purpose of this effort was to report research in three areas: to develop basic understanding of human body kinematics of the seated operator in his workspace, to define the dimensions of his workspace, and to develop basic data and plans for realistic drawing board and three-dimensional demonstration manikins. In the space requirements report and others that followed (Dempster, Gabel, & Felts, 1959; Dempster, 1961, 1965; Dempster & Gaughran, 1967), Dempster and his colleagues explicitly described the link system of the human limbs, thus introducing a concept of internal anthropometry that has proven of immeasurable value to the crew station designer. The link, briefly, is the straight-line vector extending from one functional joint center of the body through the adjacent body segment to the next functional joint center. In providing dimensional data on the link system of the human limbs as well as ranges of movement in the involved joints, the engineer was given a powerful three-dimensional design tool. In 1964, Dempster, Sher, and Priest published the necessary conversion scales to estimate link lengths of the arms and legs, based on easily measured anthropometric dimensions. Dempster specifically stated that equivalent information on the human torso was urgently needed and that it would be quite difficult to obtain.

Basic data on joint mobility gathered by Dempster, but not completely reported by him, were reanalyzed and published under the title, *Statistical Evaluation of Joint Range Data* (Barter, Emanuel, & Truett, 1957). In this report, data on 43 joint movements were related to physique. Twelve (28%) were found to be significantly related. Emanuel and Barter (1957) measured and reported the linear distance changes occurring over body joints during movement. Using 30 male subjects, 48 linear surface distance-changes were measured over the major joints of the body. These data were primarily intended to be applied to close-fitting high altitude clothing. Nicoloff (1957) published information on the effect of clothing on joint motion. This study was followed by a Boeing (1960) study of mobility in a full pressure suit.

The crewman's reach capability has been studied at regular intervals over the years. The first study having applicability to the cockpit appears to be that of King, Morrow, and Vollmer (1947). Dempster, in his space requirements report, approached the study of reach capability in a completely different manner, reporting three-dimensional movement envelopes with the subject's hand orientation held constant. These hand movement envelopes, or kinetospheres, denoted the envelope of the maximum possible movement for a selected hand orientation. Each kinetosphere was defined relative to the Seat Reference Point. By combining kinetospheres for hand orientations in a single plane, patterns of motion called "strophospheres" were derived. A strophosphere describes the maximum movement of the hand when permitted three degrees of translatory freedom and one degree of rotatory freedom (at the wrist). Two such strophospheres were developed for the hand. These studies by Dempster and his co-workers on the reach characteristics of the seated operator were primarily to "develop an indirect approach to a functional anthropometry" (Dempster, Gabel, & Felts, 1959, p. 310).

In 1964, I published data on the outer boundaries of the grasp-reach envelopes for the shirt-sleeved, seated operator (Kennedy, 1964). Ninety-fifth percentile, as well as 50th and 5th percentile and minimum reach envelopes were described on the basis of 20 selected subjects. Seat dimensions conformed to the current dimensional requirements of Air Force military standards covering cockpit geometry. The statistical reach envelopes were described by horizontal contours at five-inch intervals above and below Seat Reference Point. Similar grasping reach data (Alexander, Garrett, & Matthews, 1970) have been published on subjects wearing light clothing and various items of personal-protective equipment. In this study, the reach capability of 17 subjects was measured at 81 locations forward of Seat Reference Point. Subjects were tested while wearing personal equipment such as the parachute harness and underarm life preserver, with the K2B flight coveralls and the A/P 22S-2 full pressure suit. During the tests the subjects were restrained in their seats by a lap belt. Shoulder straps were used with an inertia reel, locked and unlocked. Subjects were adjusted to a common eye height and data gathered at selected distances from the floor. A similar, but as yet unfinished study has been undertaken by Alexander and Laubach (1972) to consider reach capability of pilots wearing Arctic flying gear. Russian investigators (Popdimitrov et al., 1969) have published selected "dynamic" anthropometry of the sitting man.

Under the joint sponsorship of the anthropologists at Wright-Patterson AFB and the JANAIR Committee, the University of Michigan Highway Safety Research Institute has completed (Snyder, Chaffin, & Schutz, in press) and partially reported (Snyder, Chaffin, & Schutz, 1971; Chaffin, Schutz, & Snyder, 1972) a study to derive dimensional data on the link system of the human torso and to relate these data to conventional anthropometric dimensions.

The intent of this research has been to complete the link system utilized by Dempster and his co-workers. In the torso-link study the positions of the centers of joint rotation were determined relative to easily palpable surface landmarks with the torso in a basic seated position using the standard USAF 13° back angle and 6° pan. These locations were then measured again at intervals during typical movements of the torso. The vectors and distances from surface landmarks to underlying joint centers, as well as from the various joint centers through adjacent torso segments to the next joint center were described for each of the several torso positions. Similar measurements were also made for selected movements of the head and neck. Finally, the entire link system of the torso was referred to Seat Reference Point. It is now possible to combine the work of Dempster on the limbs with that of Snyder and his colleagues into a single, complete system of links for the segments of the entire body.

ASSESSMENT AND CONCLUSIONS

What can one say about the current status of anthropometric and kinematic data? At regular intervals, anthropologists witness a startled reaction when they rather casually mention that 184 dimensions were measured on each of approximately 2,400 subjects, as was the case in the 1967 Air Force survey. People invariably say, "I didn't know there were so many things that could be measured." Or they ask, "What in the world do you do with all those measurements?" It is understandable that this would seem to be a large number of dimensions, especially to a mineralogist or to a bridge builder. It would seem to be a smaller number to an automotive designer. To a clothing manufacturer it would not appear to be an unreasonably larger number. To a group consisting of pressure suit manufacturers and space shuttle crew station designers, it may appear to be just about the right number. In fact, very few dimensions measured in the course of the major military surveys have not seen frequent use.

Over the years, the number of dimensions measured in the large surveys has increased. This is a direct consequence of the growing number of uses as well as users. Then, too, in planning any large-scale survey, measurements are invariably added in an attempt to anticipate future requirements. This procedure has been quite successful, but even at that, requests for information on dimensions on which there are no data, are still often received.

It is because of this latter fact, and because of the necessity to update anthropometric data, that I must say we may *never* see the day when we permanently have sufficient data and need never again conduct large-scale surveys. The Air Force flying personnel measured in 1967, for instance, differed in a number of important respects from those measured in 1950. For instance, the 1967 weight was 10¼ pounds greater than that in 1950. Hip breadth, sitting was nearly a full inch greater. Stature was nearly 3/4 inch greater and eye height, sitting, nearly ½ inch greater. As a result of this increase in eye height, sitting, the Seat Reference Point to the cockpit eye line as specified in MIL-STD-1333 (Cockpit Geometry, Department of Defense, 1969a) and MIL-STD-33574, 5, and 6 (Basic Cockpit Dimensions, Department of Defense, 1969b, c, d) was increased by 0.5 inch to 31.5 inches. Such dimensions as sitting height, buttock-knee length, and knee height, sitting, to name just a few, are extremely critical in determining the basic vertical and fore-and-aft ejection clearance dimensions in the aircraft cockpit. Such dimensions are constantly being assaulted by the airframe engineers and defended by the human factors people. Up-to-date data must be available if we are to satisfactorily accommodate the ranges for such dimensions among the various using populations. That this is true was pointed out by Lodge, in 1963, who ascribed the increase in aircraft accidents in the Navy to the use of out-dated anthropometric data on another military population in the design of Naval aircraft. He said the following: "It is *not* a contention of this report that a pilot's stature in itself produces accidents. The real point at issue is the fact that the cockpit dimensions of existing Navy aircraft simply do not match the bodily dimensions of a large proportion of the Navy pilot population. ...tall pilots have an accident rate significantly worse than that to be expected if height were not a contributory factor. Correspondingly, short pilots have a significantly more favorable rate. ...Appreciable savings in terms of combat readiness, lives, and equipment hinge upon recognition of the importance of anthropometric components in weapons systems. For instance, during the 40 months covered by this report, jet pilots exceeding 72 inches accumulated 37 accidents (or 5.5%) more than normal expectancy. On an annual basis, these figures would represent more than 11 accidents having a total cost over $7 million and involving two or more fatalities" (Lodge, 1963, p. 4).

I *do* believe that we are currently in very good condition insofar as concerns the basic conventional anthropometry on our using military populations. However, because of the requirement to update this kind of information at regular intervals, this is only a temporary condition.

Insofar as concerns the functional anthropometric and kinematic data, the case is quite different. In these areas, we find

ourselves terribly short in data useful to the cockpit designer. This condition, it appears, was brought on by two developments: the coming, regular use of computers in cockpit design and the advent of the very high-performance, high-g, aircraft and their high-acceleration cockpits. These two advances have forced us to reexamine the status of our information in a number of areas. In functional anthropometry and in human kinematics we have found immense holes in our data. Attempting to simulate, on the CRT, movements typical of those of the pilot has produced data requirements on characteristics of human movement that go far beyond our current knowledge. For instance, it was the sudden unavoidable requirement for dimensional data on the link system of the human torso that led to the previously described research at the University of Michigan's Highway Safety Research Institute. Now that we have better dimensional data on the link system, it is necessary to develop a body of data on typical paths of movement of the combined link system during typical cockpit activities. Attention must be paid to movements of the hands and arms, the feet and legs, as well as the head. Typical levels of restraint must be considered as well as different g-levels. Evaluations of the encumbering effects of personal-protective equipment must continue. Above all, these must all be considered in light of the combat environment. A great deal of anthropometric design effort is expended in providing for the takeoff, landing, and cruise flying conditions and not enough for the ultimate mission of the aircraft. At an Aircrew Station Standardization Panel meeting a few years ago, many of you heard General Robin Olds, then Commandant of the Air Force Academy, make a very strong plea for more consideration of the combat environment.

The second development that demands new anthropometric and kinematic data is the high-g aircraft cockpit. For the first time we have aircraft with higher thrust than weight. High $+g_z$ loads can be maintained for significant lengths of time during the combat period. Suddenly our crew station work-envelope standards guiding the design of conventional cockpits are of considerably less or no value to the designer. Those military standards specifying single, inflexible dimensions of the cockpit are now violated more than they are observed. We are suddenly faced with the realization that all the functional anthropometry, all the philosophy concerned with the location and actuation of controls, all the data regarding human strength, essentially all anthropometric and kinematic data based on the 13° to 15° back angles must be reexamined in light of the requirements brought on by back angles as great as 65° to 70° and high, relatively long-term accelerations.

The advent of these severe back angles, with the associated requirement to operate during high-g accelerations, and the mammoth amounts of human body size and kinematic data needed in computer-aided design, have produced a tremendous challenge as well as an opportunity for those interested in contributing the basic data which are essential to good crew station design.

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DISCUSSION ABSTRACT

• *CDR Hartranft, Naval Air Systems Command:* I would like to draw a parallel to the problem of designing a crew station that would satisfy both USAF and Vietnamese pilots. Gentlemen, the women are here; and they are going to be flying. There is no getting around it. Women are shorter in sitting eye height and a lot shorter in leg length, but their torsos are proportionately longer. Is the Air Force or anyone else looking into the problems this will create?

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* Anthropometric data have been gathered on Air Force women. The specifics are described in the written version of my paper.

• *Dr. Hitchcock, Naval Air Development Center:* The timely acquisition of the data necessary to properly accommodate the female pilot might prove to be impossible. Intuition gives rise to the belief that the female seeking and achieving flight status will not be representative of the current Air Force female population. Therefore, the population of female pilots cannot be measured until after it already exists. Of course, it will be difficult to bring this population into being unless the equipment is ready for it to use in qualification and training, so we do have a problem here.

• *Dr. Bernberg, Litton Systems, Inc.:* With the large number of F-4s that we have sold to the Japanese, has anything been done to accommodate the large difference in anthropometry between the Japanese and American pilots?

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* Once an aircraft is off the assembly line there is not much you can do to retrofit for an extremely different population. We have all heard about the foot blocks on the rudder pedals and the special seat cushions that Vietnamese pilots are using. I would imagine the Japanese are doing the same thing. Aside from that, the F-4 and many other first-line aircraft have some serious problems in accommodating American pilots. If we find these problems in the U. S. Air Force, they cannot help but be exaggerated in some of the other populations. Unfortunately, the Western populations, the largest anthropometrically, are designing and manufacturing aircraft and selling them to the rest of the world, who are invariable anthropometrically smaller.

• *LCOL Boren, USAF Aeronautical Systems Division:* The comments regarding both the need of updated anthropometric data for the U. S. and foreign populations are well taken. However, I note that on the practical side of systems development, we do not use the data *now* available because of the overshadowing emphasis on hardware. I think we should seek specific, realistic suggestions for increasing recognition of human factors considerations. The question of getting support to put the man-machine aspect of systems in proper perspective underlies every other dilemma.

• *Dr. Jones, McDonnell-Douglas Corp.:* My comment relates to the timeliness of anthropometric data. If such data had been available to the designers of the F-4 many years ago, they could have had some impact on the aircraft design. But the availability of anthropometric data tends to lag considerably behind our requirements. Comment on that, and maybe this group could help you anticipate these data requirements better and get the funds to go meet them.

• *Mr. Bittner, Naval Missile Center:* I agree. The 1980 population of Army, Navy, and Air Force is already more than half grown. Is it not possible to develop anthropometric data on this population, as well as functions which relate measures at one age with those at another? In other words, can we not extrapolate presently available anthropometric data to estimate tomorrow's population of potential aircrew members? Why has this approach not been applied?

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* Data lag is always a problem, not only in anthropometry but throughout the sciences. But you are perfectly correct that we are always using essentially out-of-date anthropometric data. The question, I suppose, concerns the significance of the differences between the current population and the measured population. I do not really know what can be done about this. Attempts are being made to project into the future, certainly as far as 1980, to estimate the values for some of the more important dimensions. There is a big question in my mind, however, about how accurate we can expect these projections to be. I seriously doubt that a straight line drawn between the values for stature, for instance, in the 1960 and 1967 Air Force surveys and extended to 1980 would suffice. In addition, we do not know, at this time, what our selection criteria for military pilots will be in the future. We suspect for instance, that the South Vietnamese Air Force selects its people using far stiffer criteria than the Army, and so invariably ends up with larger pilots than population statistics would suggest.

• *Mr. Lazo, Naval Air Development Center:* One of the big problems that has resulted in the lack of accommodation in the F-4 has been the series of seat modifications. The body positioning that was dictated for the F-4 in its early design stages has now been radically changed. I think it should be emphasized that original body positioning should be maintained in any future design modifications. But the question I have in mind is this. We have been specifying designs relative to a fixed segment of the population, such as 5th to 95th percentile, instead of the full population. What are your thoughts on the efficacy of this approach?

• *Mr. Stanton, NASA Headquarters:* I would like to expand that question. Why does the military in particular design for 5-95 percent man? Why not restrict it to 15-85 percent as there are sufficient flying or crew candidates available in the United States to satisfy military requirements. If the specifications were changed to 15-85 percent, for instance, then some anthropomorphic problems could be eliminated, and cost effectiveness could be improved. With the advent of remote-piloted vehicles over the horizon, changing specifications now, before the ground-based cockpit is designed, seems highly desirable.

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* There is one philosophical problem associated with measuring a military population, designing for one segment of that population, and letting the rest just get by as best as they can. If we design for the 5th to 95th percentile among flying officers, what about that extra ten percent who are also flying? If the human body were as rigid and uncompromising as machines, we could very

efficiently throw out ten percent of the flying population. Fortunately, that ten percent can squeeze and stretch and do things that machines cannot do, so they can be retained as flyers. But, philosophically there is something wrong with measuring the population, designing things for only 90 percent of that population, and then years later redesigning for the remaining ten percent.

• *Mr. Atkins, Vought Aeronautics:* The F-5E was procured by the Air Force specifically for use by foreign nationals. Do you know how the anthropometric problems were handled?

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* I was invited to participate in the F-5E program, but we were told in no uncertain terms, "Look fellows, don't make any changes." Now, how well the Vietnamese are utilizing this aircraft, I just can't say.

• *Mr. Mancinelli, Naval Air Development Center:* These comments are the kind we have heard for the last 20 years--I hope this conference will stop talking about what we failed to do and why we failed to do it and start talking about what needs to be done now and how to do it better.

• *Dr. McGrath, Anacapa Sciences, Inc.:* My comment is similar. You began your discussion, Ken, with several examples of horrendous design errors involving anthropometric issues. All of those errors seem to have been the consequences of not using the anthropometric data that were available. But our discussion seems to be pointing to the conclusion that we do not have the needed data. So, what is the real problem? Do we lack the data or are the data just not being used?

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* I can only speak for the Air Force and for our very small anthropometry staff. We believe we have a program that could be fantastically beneficial to the pilots. On the occasions when we go to the field and work with the pilots on their specific problems, they are invariably elated to find out that there really is somebody back there who is concerned about their welfare. I firmly believe that our small unit could be greatly enlarged and still find more things to do to help the pilot than we could possibly take care of. I think this same kind of an organization could be established in each of our military services. They need not be anthropometrists, they just have to be people who appreciate the problems of flying, the variability of human body size, and the effect of these factors on design. We have to create a body of people to do the work. One of the purposes of this meeting is to somehow recognize these problems and feed them to the people who can do something about them.

• *CDR Lassen, Naval Safety Center:* I hear you describe all the measurements that are being made on pilots, but I am wondering whether you are taking into account the different ways a pilot can sit in his aircraft. For example, I set the seat differently for instrument flying, for weapon delivery, or for carrier landing--always using extreme positions on the seat adjustment. I need to change my position considerably when I am flying, so if you could just provide much larger ranges in rudder and seat adjustments--much larger than you think you would need on the basis of anthropometry alone--you would be on the road to a solution.

Also, when you say to a pilot, "I want to measure you, sit down," he is going to sit erect. But that is not how he flies. When flying, he is hunched forward and is sitting much higher than the aircraft's design eye position. In fact, he is likely to be hurt if required to eject while sitting in this position. I am wondering if you ever measure this type of sitting rather than the "perfect gentleman" type.

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* This kind of measurement is very difficult to do in large-scale surveys. But, at least we have a program underway at Wright-Patterson AFB in which we will make photogrammetric analyses of the functional positions of body parts in typical flying attitudes. These include the body position when using the head-up display, the sights, and other pieces of equipment that force the man to change his body position in order to operate.

• *Mr. Jahns, Forschungsinstitut fur Anthropotechnik*: Perhaps more could be done to train (or point out) to pilots the optimum body positioning for various flight tasks to help solve this problem.

• *Mr. Moreland, Army Aviation Systems Command:* We have recently encountered two problems in this area. One is that we lack up-to-date information about the equipment worn by Army aviators in different environments. For example, when a helicopter pilot must wear an armored chestplate and a survival vest, he encounters definite problems in getting full throw on the controls. We looked throughout the Army for good data on this and found none.

The second problem is the need for bivariate distributions. We do not get the typical 95th percentile pilot, we get a guy with a 95th percentile sitting height and a 5th percentile arm reach. I think bivariate distributions of anthropometric variables are going to be of great improtance to us in

cockpit design. I would like your comment on that.

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* The only way you can determine how encumbering personal equipment on the pilot affects his ability to operate his aircraft is to have somebody measure the pilots at the airfield. We have done this with the K-2B coveralls, the underarm life preserver, and the A/B 22S-2 full pressure suit. We have completed the first half of a similar study on Arctic flying gear. We will then go to Iceland to measure the people in the equipment they actually use. I do not think you can ever get this information from any kind of office; you have to go out and measure it.

Bivariates are instructive because they show the distribution of values on one dimension with respect to the values on another. But, in cockpit design, I have never found bivariates terribly useful in themselves. I much prefer to use percentile data, even though it is true that 95th percentile dimensions, when added together, lead to something pretty gargantuan because there is no such thing as a 95th percentile man. In fact, 95th percentile values cannot go together on the same individual. Bivariate distributions are very useful in designing and sizing clothing, but I have never found them particularly useful in cockpit geometry work.

CREW STATION CONFIGURATION

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Abstract: *The development and design of modern crew stations and operator workplaces suffer often from compromises which are the result of system considerations outside of the crew system area and often lead to poor performance by the operator, or worse, to accidents or mission failure. In order to assure that the crew station design incorporates the proper consideration of all aspects, including the human operator, design must not only be optimized, but also be backed by valid and readily available data. In addition, rapid evaluation methods must be available to determine the effects of any changes on the crew station configuration. New methods, particularly in the computer-aided design field can help to alleviate these problems. Inexpensive and rapid mockup construction techniques will allow better evaluation. But considerable effort must be expended to perfect such techniques and to make them readily accessible to the designer. This includes also the improvement of currently available data, data formats, and requirements. Such data must be developed to meet the challenges not only of conventional designs, but also new and different systems which are now under consideration.*

INTRODUCTION

The preceding papers all have dealt with aspects of the crew system which are vital to the efficiency and safety of the operator of a system, wherever it may be used and whatever its purpose. However, the best display, the finest control, or the safest and most reliable escape system loses its effectiveness if it is not arranged in such a fashion that it can be used by the operator in the fulfillment of his tasks. Thus, the design of the workplace, or more specifically, the design of the crew station must be regarded as a crucial element which integrates all the components, including man, and synthesizes a space within which he can function efficiently and safely. While this sort of statement should not meet with great opposition, unfortunately, the experiences of the past have shown that such integration and synthesis is either not always feasible or sometimes just poorly executed. In the end, the user of the equipment must adjust to the equipment and its problems rather than the other way around. Thus, we can read in a recent IFALPA publication the following description of the working pilot (Masland, 1963).

"The pilot is strapped in place behind the controls wearing ear phones and the long cord that hangs from them, wearing an oxygen mask on his face or hanging against his Adam's apple with the supply tube tangled with the phone cord. He is approaching his destination. He has five charts, three of them the large, folding type on his lap or disposed about his person. He has route manuals and a cruise control book immediately available; in addition to the weather folder as originally issued, he has a notebook full of spot weathers and revised forecasts, clearances and revised clearances, on his lap or otherwise dispersed about his person. He has a set of *Notices to Airmen* containing the latest modifications to route and terminal facilities also located somewhere about his person or environment. And he doesn't even have a place to put a pencil, let alone a desk on which to use it. To suggest that someone can run a million dollar business from such an 'office' is preposterous. It is done, but no one ever figures out how. It must be changed."

How does it happen that such complaints can be heard no matter what type of vehicle we are talking about and no matter what its purpose? Surely, the problem is not one which has gone unnoticed until recently. Let me quote from the 1946 edition of the *Handbook of Instructions for Aircraft Designers* (AFSCM, 1946):

> "As aircraft become more complex, and as their performance characteristics make greater demands on the physical and mental capabilities of the crew, the designer must recognize and cater to these definite limits lest the best conceived aircraft from the mechanical, aerodynamic or tactical standpoints fall short to the extent that it makes inordinate demands on the flyer" (Para. 0.12).

Man's limitations and capabilities must be taken into account together with the mission requirements and the environment in which the mission is to be performed. The problem here is to develop a crew station which can be operated safely and efficiently by regular service or commercial pilots without an excessive amount of training or risk. This aspect of the problem has not always been answered successfully. It is the routine operation which must dictate the design of the crew station.

Not only must the displays and controls be designed to allow efficient operation within the crew's capabilities, but a host of other factors must be integrated to arrive at a cost-effective solution. Among these are: pilot vision, escape and survival, seating, internal and external environment, ingress/egress, lighting, anthropometrics, battle damage/protection, communications and navigation, pilot incapacitation, computation, flight control, and failure warning. In short, the operations, environment, and crew factors must be included in the development of the crew station configuration.

THE DESIGN PROCESS

Crew station configuration, like any other part of a system under development, should follow the same design process. Starting with studies during a conceptual phase, it should progress through preliminary design and analyses to progressively firmer design until the basic design is established and production initiated. Finally, during the operational phase of the system life cycle, continued support for modifications and changes is required. We will focus our attention on the earlier phases of the cycle, since it is during those early phases that most of the design decisions and compromises are made which are then reflected in the complaints of the users. If such a complete cycle could be followed systematically, and all the necessary data and requirements firmly established prior to the initiation of the final design, then the resulting crew station should be about as optimally designed as feasible. To find means and ways to make such an achievement possible is, in my opinion, one of the major goals of this gathering.

The main objective of any design is to satisfy a set of requirements. Thus, unless all the requirements are clearly defined and sufficient analyses have been conducted to establish their validity, all design efforts are doomed to failure from the start. Requirements can be established in a great variety of ways, starting with those specified in the initial documentation of the eventual user, formal system documentation, other source data or experimental tests. Hopefully, prior to the beginning of the design phase, sufficient analyses have been conducted to identify the mission requirements, the mission profile, the allocation of function between man and machine, the action and information requirements and associated crew tasks as well as other constraining factors which generate requirements. In one form or another, all the areas you have heard discussed at this conference generate requirements which impact greatly on the ultimate packaging effort, in other words the crew station arrangement. If any one of the areas falls behind in the generation of requirements and the transmission of these requirements to the crew station designer, then mistakes can be made which result in costly delays and re-designs.

The analytical requirements must then be translated both into design requirements or criteria and into design concepts which meet the analytical requirements.

The transition from the analytical results through complete system synthesis and man/machine integration to one or more viable crew station configurations worthy of evaluation is a process involving both scientific logic and art. In this process, the solution elements which have been defined in detail functionally must be mated with elements of technology which can provide the capability of meeting those functional requirements. Where no such technology exists, critical trade studies must be conducted to compare the penalties imposed by altering the requirements against those imposed by forcing an advancement in technology. Once technical solution elements have been identified, the next step in the process is to translate these elements into a single, working hardware concept. This is perhaps the least definable, and yet most important, portion of the cockpit evolution. It is here that the desires of the operations analyst, the human engineer, the hardware design engineer, and the pilot all must be satisfied with a single solution. Consequently,

the process still remains as much a subjective art as an engineering science, and the realistic subjective evaluation of operational hardware concepts is of paramount value in the attainment of design acceptance. It is anticipated that improved methods for changing task information-action requirements into total crew station design criteria would further the development of crew station design as an engineering science.

Given an aircrew and a hardware complement, each with finite capabilities, there still remains the task of integrating these two elements with other design and configuration requirements to produce a practical cockpit configuration which will pay off in terms of improved operational capability. Requirements which include consideration of such aspects of cockpit configuration as internal and external vision, anthropometrics, seating, ingress/egress, escape, ambient and internal lighting, crew protection efficiency, and comfort, all must be addressed and reconciled in the process of designing total cockpit conceptual layouts. The application of formalized trade study and optimization techniques becomes a staggering task because of the number and type of variables in such a multi-dimensional evaluation matrix. Thus, heuristic reasoning and subjective evaluation play important roles in arriving at a solution. It is easy to understand from a practical standpoint how minor variations in these factors might have far-reaching implications, and may indeed produce several cockpit configurations which have some degree of commonality, but yet enough variations to merit evaluation on a non-competitive basis. It is equally easy to understand why, over the past 20 years, cockpit improvements have been more evolutionary than "revolutionary" in nature.

DESIGN REQUIREMENTS AND CRITERIA

Design criteria must be developed for factors other than displays and controls to achieve complete crew station design criteria. These include pilot vision, escape and survival, seating, internal and external environment, ingress/egress, lighting, anthropometrics, battle damage/protection, display and control arrangement, pilot incapacitation, computation, flight control, etc.

Pilot vision involves the development of field-of-view and visual-range requirements for all aspects of the mission. Trade studies involve airframe nose configuration and drag penalties, windshield materials and coatings, defogging/clearance, deviation and distortion, glare, seats and seat arrangement, approach and landing paths, landing and delivery (be it of passengers, cargo, or weapons) area characteristics, display-control location, and airframe dynamics and characteristics. Both analysis and simulation tests can be required to effectively resolve the problem of specifying a viable set of vision requirements.

Escape interactions involve seating, crew station arrangement, and the mission envelope. An initial trade study must resolve whether or not an inflight cockpit escape is to be included. Battle damage survivability design techniques are rapidly improving such that hits that would normally destroy airplane and crew may be sustained. One has to project damage design techniques and relate these to expected damage from the forecasted environment. Equipment reliability enters into this problem, and must be considered as a key variable in determining if an escape system is required and what type. Based on these considerations, escape system design criteria must be defined.

Seating requirements interact with environment considerations such as turbulence, mission endurance, number of missions per day, anthropometry, escape, crash loads, ingress/egress, control and display layout, pilot/copilot access to each other, and personal gear. Trade studies involving all of these variables interacting within the context of tactical mission requirements need to be performed.

Ingress/egress must consider normal operations as well as evacuation and escape. Overall cockpit arrangement, seat design and crew motion, panel and console slopes, aisles, doors and hatches all impact on ingress/egress geometry. Trade studies involving mockups are required to develop proper requirements for these relationships.

Anthropometrics, both static and dynamic, are a key consideration in cockpit layout. The wide variation in size, shape, and motion characteristics of crew members significantly impacts the location, shape, and integration of all cockpit elements. Anthropometrics need to be considered in conjunction with the ergometrics of man's force-producing capability.

Battle damage considerations (where applicable) will influence cockpit arrangement and possibly crew mobility. Personal armor, seat armor, hardened windshields, and the location of equipment modules are interrelated variables of crew protection. Trade studies and design concepts which account for these need to be done before crew station design criteria are finalized.

In multiplace aircraft, pilot incapacitation is a key factor when integrating displays and controls, arranging the cockpit, and assigning tasks. Care must be taken to ensure that the tactical mission can be completed by one pilot in the event the pilot or copilot cannot share in task performance.

This consideration must thread throughout the analysis, mockup and simulation test phases of the development program.

The foregoing points out the complex interaction of a large number of variables and trade studies that must be considered in developing crew station design criteria. This task must be approached systematically to identify all relationships, and control the development of a large body of data. Analysis, mockups, part-task simulation, and full-mission simulation will be required to successfully accomplish the task.

CREW STATION LAYOUT

Once the control/display hardware is defined, the cockpit designer can proceed with the process of crew station layout. Extreme caution must be exercised at this point, for it is here that the designer can become so dazzled by the glamour of advanced control/display technology that the primary functions of the aircrew fall into the shadows. As a result, controls/displays tend to dominate the cockpit design, often at the expense of other important design features. This situation is evidenced in almost every large military and commercial aircraft, where tremendous areas of crew station space have been eaten up by displays, dials, instruments, handles, knobs, and buttons, leaving the crew with only small glass slits to serve as mini-windows to the outside world. The designer must always bear in mind that the crew of an aircraft has two primary functions--the control of the vehicle and its subsystems to assure operation within safe and effective limits, and the pursuit of assigned mission tasks requiring additional activities beyond basic vehicle control.

There are many factors which affect the crew's capability to perform these two primary functions. Within the cockpit layout area, these factors are influenced by design characteristics which can be categorized into three different but interrelated groups: safety, effectivity, and comfort. To understand the relative importance of these factors, perhaps several examples would be helpful. For instance, the aircraft of World War II were designed with the factors arranged in the order effectivity, safety, and comfort. It was expedient to design a vehicle to do a job. In situations where crew safety could not be guaranteed, an alternative (usually parachutes) was provided. It was equally expedient to make comfort a last consideration. After all, getting the job done was the important thing, and crews accepted moderate compromises in safety and sizable compromises in personal comfort to accomplish that goal. In contrast, let's look at the world of private and business aviation. Here, the tendency seems to be to arrange the factors in the order of comfort, safety, and efficiency. Given their choice of a plush interior or a redundant (twin) engine, many executives choose the plush interior, all other things being equal. While such reactions have been attributed to the feminine influence in the case of the private aircraft owner, the important observation to be made is that human motivation plays a vital part in the relative significance which any individual attaches to safety, effectivity, and comfort.

Controls and displays required for performance of critical flight and mission tasks must be studied and configurations recommended which impose the minimum visual and tactile accessibility requirements. Both continuous and discrete control functions are analyzed to minimize the number and extent of control motions. If control displacement and reach envelopes can be reduced without compromising safety, reduction in the size of the crew station envelope may be possible.

Assuming that adequate task accommodation has been provided, perhaps the next most important effectivity factor to consider in cockpit design is vision. Generally speaking, state-of-the-art transparent windshield material is heavier and more expensive than non-transparent material. Consequently, it is advantageous to keep transparent areas to a minimum. Existing standards pertinent to cockpit vision, such as MIL-STD-850 and MIL-STD-1333, are more a reflection of evolutionary accomplishment than of actual requirements. However, documented research establishing minimum transparent areas for new aircraft such as STOL-V/STOL aircraft is practically nonexistent. Everyone admits that location of design eye position, visual angles, and obstructions to vision all can have significant effects on performance. But because man is so adaptive, little effort has been expended to establish actual minimum requirements of optimum vision configurations for the accomplishment of the two primary aircrew functions. For the non-hostile environment, a general feeling prevails that the more you can see outside the cockpit the better. But the design of a safe, efficient and practical cockpit, requires trades of vision versus cost/weight if the system is to be optimized.

Another influence which must be taken into account from the very start is the personal protective equipment for the pilot, particularly the addition of a full pressure suit. If such equipment is not taken into account during the initial layout, the designer can find himself in the embarrassing position that his eye reference point has slipped by more than two inches when the pressure suit is added.

In the field of anthropometry, we have progressed from no concern about the size of the aviators, except maybe that he was too

heavy, to designing crew stations for the 50th percentile operator, probably under the assumption that, by using his measures, at least nobody on either side was being unduly favored.

More recently, aircrew station design efforts have centered about accommodation of the aviator's 5th-95th percentile dimensions. The reason given most frequently for exclusion of the first through fourth and 96th through 99th percentile dimensions was, and still is, that accommodation would be prohibitively expensive.

Today we find that Navy design requirements will specify that the population for which the system is designed should include all sizes from 3rd to 98th percentile.

The accommodation of worst cases of clothing and personal equipment must be considered. Further design considerations must be based on the most recently available aviator anthropometric data to accommodate the increased dimensions in the latest generation of aviators and/or nationality, as pointed out in Mr. Kennedy's paper.

The design configuration must be such that impairment to normal ingress/egress is minimized. Seating, seat articulation, restraint, and crew arrangement optimized for ingress/egress without degrading reach and vision requirements for individual and shared equipment. Care also must be exercised to design the cockpit system so that emergency ingress/egress--after a survivable crash--is not impaired. A crash-survivable cockpit is of little value if the aircrewman is pinned in the seat or cockpit after the crash.

An additional objective of the cockpit layout process is to identify worthwhile techniques for providing ballistic protection for the aircrew and their critical man-machine interfaces. If such is required, the problem resolves basically into three questions: What kind of protection? How much protection? And where should it be located? Consideration of kinds of protection and armor materials will be treated. Obviously, the answer to the question of how much protection could vary anywhere from no protection at all by dangling the aircrew in space in an aluminum and plastic bubble to 100% protection by complete encapsulation of the aircrew and its man-machine interfaces in hunks of transparent and non-transparent armor. Common sense tells us that the first extreme offers little in terms of combat survivability. At the other extreme, we reason heuristically that armor is heavy and expensive, so we want to minimize the volume of armor material which must be employed. The problem then is one of finding that configuration of materials and locations which provides the maximum ratio of protection to volume of armor. Quantitative assessment of protection and armor volume is dependent upon such factors as threat type, azimuth and obliquity angles of ballistic impact, velocity at impact, etc.

There are several other protection factors which affect safety and merit consideration in the design of an aircrew protection system. For example, each aircrewman must be provided with a crash-survivable seat and restraint system. We know from experience that merely layering ballistic protection onto a crash-survivable seat poses some problems, the major one being that the seat must be designed to accommodate the additional weight of the armor under the specified g-loads. Attention must be given to integrating the ballistic protection with the crash-survivability protection to produce a simpler and lighter weight solution to the two problems. Associated with crash survivability is the problem of cockpit delethalization. While complete encapsulation of the cockpit with armor provides ballistic protection, it offers no protection to the aircrew against the flying knobs, handles, lights, and other hardware which frequently ricochet about the cockpit during a potentially survivable crash.

The tensions of flight, particularly in a hostile environment, tend to produce higher pulse rates, blood pressures, and respiration rates within the aircrewman. These tend to increase the rate at which fatigue accumulates. Wrapping an aircrewman in armor, and surrounding him with heat-generating controls and displays so that body heat and perspiration cannot be dissipated, contributes further to degradation of performance. Ultimately, particularly in low threat situations, crewmen have been known to "strip down," sacrificing safety and protection for the comfort of cooling and ventilation. Consequently, it is imperative that ventilation and temperature control be taken into consideration in the design of the protective system. Environmental control requirements will be developed and design concepts generated for inclusion in the Phase II design effort.

Similarly, noise and vibration at the aircrew station historically have contributed both physiologically and psychologically to fatigue, with the end result being degraded performance. Consideration will be given to integrating acoustical and vibration-reducing properties into the cockpit system wherever practicable, in an effort to conserve weight and space.

CREW STATION EVALUATION

So far, we have mentioned some of the considerations in the process of developing crew station configuration, starting with the analytical efforts and proceeding through the

design of actual crew stations. We now must turn to the problem of crew station evaluation, that is, the determination of how well the requirements have been met by the proposed design solutions. Such evaluations are performed in every phase of system development and on elements, components, subsystems, and total systems, involving both equipment functional performance and crew performance. Just how valid such evaluations are depends on the background, experience, and skill of the evaluator; the quality of the criteria used; the evaluation methods and their limitations; the type of testing and evaluation to be done; and finally, the fidelity and quality of the test equipment. The evaluations may proceed from the simplest evaluation of drawings based on analytical studies and simple simulations, to computerized mathematical models, to mockups, fixed-base and moving-base dynamic simulators, finally to flight testing.

The problem lies in the fact that the early evaluations have less validity than the later ones, such as full mission simulation and flight test, and yet most of the decisions relating to the crew station must be made early in the program when re-design is still both feasible and less costly. Once the design is frozen and manufacturing commitments are made, changes become excessive in both cost and time/schedule commitments. In addition, the procuring agency, whoever it may be, must make commitments which are far-reaching and expensive in the selection of proposed configurations, even though these configurations are based on the output of limited evaluation tools. Faced with these dilemmas, let us look briefly at the status of evaluation as it is currently practiced.

Drawing reviews, mockups, mathematical models, flight simulators, and prototype flight test techniques are used to evaluate crew station configuration.

Drawing reviews using information on cockpit drawings, usually consist of comparing proposed dimensions and display/control positions with those recommended in military and FAA standards and specifications. Handbooks, such as the *Air Force Systems Command Design Handbook, Series (DH)*, are used along with basic anthropometry tables to provide detail criteria. A few special tools have been developed to reduce the flow time and cost of these reviews. Slide rules that summarize anthropometric data and two-dimensional manikins that can be quickly adjusted to flight-crew population limits have become an accepted part of the cockpit engineer's tool kit.

Link analysis is sometimes performed as a part of the drawing review. This technique is quite laborious and tedious to apply for each geometry concept being evaluated, and consequently is not used as often as it should be. Today, however, it is the only way we have of measuring crew physical workload. This analysis identifies most-traveled links, both visual and crew appendage, between the various cockpit subsystem elements. It can also provide a summation of total appendage and eye/head deflection travel as a function of mission task. Thus, link analysis, properly performed, is the basis for optimizing the location of cockpit elements in terms of minimum crew physical activity.

Drawing reviews are useful for preliminary evaluations. They provide the only evaluation data early in design programs, and many geometry errors are identified by this simple method. The method is limited by the evaluator's ability to visualize three-dimensioned dynamic flight-crew physical activity, by the time required to draw special views, and by the engineer's ability to apply the large mass of anthropometric and ergometric data.

Mockups supplement drawing reviews. They are excellent communication tools for review teams, and permit evaluators to try out a design concept. Evaluators can easily simulate, in non-real time, the intended physical task sequences of flight-crew members and can more easily identify configuration problems with mockups than with drawings. The mockup is an indispensable tool for cockpit engineers.

The dollar and flow-time costs for mockup construction have improved over the years. Three materials are generally used for mockups today: metal, wood, and Fome-Cor. The comparative costs of simple tandem cockpit mockups made of each material are summarized in the following table.

MATERIAL	MAN-HOURS	MATERIAL COSTS
FOME-COR	300	$300
WOOD	1500	$500
METAL	3400	$750

The Fome-Cor mockup technique was developed in the early 1960's primarily by Fom White of LTV, Inc. This type of mockup has become the first mockup for geometry evaluation. Preliminary mockups can now be made available for cockpit design support with little lag time from the drawing board.

As useful as mockups are, it is still not possible to thoroughly evaluate cockpit geometry through mockups because people representative of a wide variety of human anthropometry are not available to exercise the mockup.

One additional problem should be mentioned which is often ignored and can lead to later problems. The population of the evaluators will not only differ in background and

experience, but also in size. While all attempts should be made to involve the using population as early as possible, their anthropometric characteristics should not be neglected. As yet, the *USAF Design Handbook DH 2-2* instructs in the section on Mockup Support (Ch. 2, Sect. 2A):

> "Furnish the following support to the mockup inspection: Human subjects approximating the 5th and 95th percentiles of stature and weight to design mockups. The small subject, 5th percentile, should not be taller than 65.9 inches nor weigh less than 211 pounds. Equip subjects with maximum required clothing such as pressure suits, ventilating garments, and exposure suits, and with maximum required personal equipment such as parachutes, life preservers, and survival kits. Use subjects to assure that aircraft design permits performing assigned duties, and adequacy of design with regard to comfort, efficiency, vision, escape, maintenance, lighting, environment, entrance and passage-way space, safety, and related human engineering considerations."

This type of instruction obviously ignores the problems of sitting height, reach, etc., mentioned in the earlier paper on anthropometry.

Let me now turn briefly to the computerized design aids such as they exist today. Basically, three major areas have been attacked for modeling on the computer: crew workload, crew station geometry, and crew vision.

Crew workload models have been discussed before and will not be repeated here. Needless to say, that such models can be of great value to the designer in that they point towards areas of possible crew overload and define for him the functions and tasks which the crew must perform. This ensures a considerably more efficient packaging of the various crew system components. While such crew workload models at this time are primarily timeline/workload estimates, they nevertheless give the designer an idea at a much earlier stage than was previously available.

Crew station geometry and man models have been intensively worked over the past five years. Developments such as HECAD, CAPA, and the CGE program are beginning to show fruit. Much more work needs to be done to bring them to the full capability, but it is a good start.

The Cockpit Geometry Evaluation (CGE) program is a Boeing/JANAIR development initiated in January, 1968, to establish standardized methods for evaluating the physical geometry of a crew station. The program is designed not only to significantly improve methods of crew station evaluation but also to make these methods available during the conceptual phases of crew station design.

The CGE developments to date have resulted in a sophisticated, yet flexible, computerized evaluation tool. The CGE Computer Program System (CGECPS) has the following major features:

- Data storage bank in which anthropometric data, crew station geometry data, and flight mission task data can be stored for efficient and flexible recall,
- Dynamic mathematical man-model, capable of assuming the anthropometric characteristics of any member of the pilot population as well as certain environmental variables (e.g., various forms of physical restraints). In addition, the man-model is capable of simulating human movement parameters,
- Reach basket model capable of efficiently analyzing a crew station design for reach infeasibilities under a wide variety of anthropometric and environmental conditions,
- MILSTAN, a computer program which checks crew station geometry compliance with applicable MIL-STD and MIL-SPEC requirements, and
- Output from all the above in a variety of formats, including computer graphics.

The dynamic man-model provides the identification of reach problems, physical interference problems, visual interference problems, possible solutions to some of the visual and physical interferences, and numerical performance indicators. With regard to reach problems, the man-model determines the dimensional magnitude of the problem as well as calculating an acceptable relocation of the control. With regard to the interference detection, the program determines what portions of the man-model and/or the cockpit are causing the problem as well as an indication of how severe the interference is. Possible solutions to the interferences are calculated. Finally, the numerical performance indicators consist of the angles of elevation and deflection subtended by all controls and displays with the Eye Reference Point (ERP) and a summation by task and task sequence of the amount of travel of each of the body segments of the man-model, including eye travel.

Such efforts will be of use to the crew station designer in three ways: first, the program will prove most valuable in the iterative evaluations and resulting improvement guidelines for the geometry design of each

crew station alternative. That is, the results from each successive evaluation will be used to correct and eliminate all reach problems and minimize the interference problems and the crew member physical workload for each design. Second, once the geometry of each alternative has been optimized and hence finalized, the CGECPS evaluation results of the finalized designs will be used in trade studies to determine the best design based on geometry criteria. A matrix of the alternate designs versus the evaluation results (e.g., interference identified, summations of body travel, angles subtended by controls/displays with the ERP, MILSTAN compliance, etc.) will be developed to aid in selecting the best designs and identifying the associated design criteria. Third, the results will provide data to the using agency for evaluation and compliance checks for final designs.

To rapidly determine the effective external visual envelope provided for the pilot from the design eye position, computerized techniques have been developed which will provide graphic plots of the visual envelope as well as numerical printouts. The purpose of such programs is to provide data for analysis of cockpit efficiency and crew vision capability. To evaluate the work imposed on a crewman, physical quantities can be measured associated with each task.

The angles, distances, and spherical excesses can be measured relative to an eye axis point and also can be measured to simulate a binocular camera. When simulating a binocular camera, spherical excess is found for the monocular, binocular and ambinocular fields. Also, the vision envelope simulating the binocular camera may be plotted with the minimum required cockpit vision envelope superimposed. This allows a rapid check for compliance with the established vision requirements and/or the vision envelopes specified in military standards. Visual surveillance outside the aircraft can be evaluated by comparison of spherical excess.

Incremental angles and distances will also give a measure of workload imposed on the crew, but the tasks incorporated in such workload must reflect both normal and contingency (degraded) mode operations.

PROBLEMS AND IMPROVEMENTS IN THE DESIGN PROCESS

In spite of all the good intentions with which a design project is approached, judging from the opinions of those who, in the end, will have to use whatever is designed, we are not producing the ideal crew stations by a long shot. At this point I would like to point out some of the problems which I see are present in one form or another in all design efforts and which result in design compromises and changes which can have severe consequences. There are basically three levels where decisions have to be made to depart from what might be called the optimum solution: at the working level, at the management level, and at the user or customer level. At the working level, beside the pressures of schedule and budget, which are always present, I believe that one of the problems arises because the designer is not always given the data which he needs to make well founded decisions for design solutions. Often, the analytical efforts are lagging behind the design and waiting would jeopardize the schedule. On the other hand, particular problems which need analysis and answers are not answered rapidly enough. To compound the problem, once data do arrive, they are not always in such a format that they can be readily used. Some of the contributions I have seen to the design groups have raised more questions than they answered. To make matters worse, even if they seem to answer the question, they are given in terms or language that is hard for the design engineer to understand. I think I am not revealing any secret when I say there still exists a certain communications gap between the engineer and those who are supposed to aid and comfort him in his efforts. This is particularly true for those of us whose main interest is the man in the system. The design engineer is supposed to be able to discourse with equal fluency with human engineers, life support experts, medical people, pilots, and whoever else has an interest in the crew station or cockpit. To quote T. V. Taylor (1962): "Many human engineers have become so preoccupied with machines that they have forgotten that the well-being of the human component is a *sine qua non* for system effectiveness. This has forced the physiologists, environmental medical specialists, and habitability experts into developing their own approaches to equipment design. Thus we find a plethora of human factor specialties, each claiming to supply a vital service to the engineer. Small wonder that the layman--and often the expert--is bewildered and confused as to what the spokesman for the man in the machine is really trying to say, since he speaks in many tongues and gives many different and often conflicting sets of directions."

Another problem lies in the efficiency with which the designer can evaluate the adequacy of his design. As we have seen, strides have been made to improve this situation, but still, in many cases the evaluation techniques of today are laborious, time-consuming, and budget-consuming. The mockup is still one of the major tools of the evaluation. And finally, there is a problem in the efficiency of the actual process of designing. The old drawing board is still the major crew station for the designer and the drafting machine his major tool. Needless to say, a time-consuming

procedure.

But more serious than the problems mentioned above, is the situation when major design decisions are reached at the management level. Here compromises must be reached between various groups and technologies, each with their own data, biases, and ideas. It seems to me that while the performance of the aircraft to its specifications is the paramount consideration for effective systems and the cost and schedule is foremost in the manager's mind, that too often drag-count wins over anthropometry and weight wins over crew efficiency. There seem to be two reasons for this. First, few program managers, if any, have any background in crew station design. Thus the arguments of aerodynamics and structures and propulsion are more familiar and appear more cogent. Second, most of these technologies are able to provide relatively "hard" data to back their arguments which the crew station designer, together with his backup crew, cannot provide. While some decisions should be made to assure adequate system performance, some are made for reasons which appear minor in the end, but which have a tremendous impact on the crew station. The decision to utilize curved windshields on one of our large transport aircraft for aerodynamic reasons has had a profound impact on the crew station, both in terms of crew vision as well as crew acceptance. It seems to me it behooves us to take a good close look at this decision-making process to see where improvements in the crew system can be achieved.

Finally, at the customer level (who inside his own house has problems similar to those described above) we find that problems exist which affect the design process. There have been cases where the intentions of the procuring agency have been vague and subject to change during the procurement process. The problem of data can be mentioned next. Specifications and other data are sometimes neither applicable or available. This applies particularly to systems which radically depart from current practices. To mention just one, the current requirements for increasing back angles of the seat are not covered by any specification, even though some data are available. Likewise, the visual field requirements for a V/STOL transport have been mentioned. In addition, it seems to me that the crew systems area is not always properly represented in program offices.

What can be done to improve the situation? At the working level, we should not only strive to perfect the evaluation techniques already mentioned, but actually try to incorporate them in the design process. Obviously, these tools must be further developed to achieve their full effectiveness. Here we seem to require two developments. First, refinement of the man-models must be continued to eventually include such features as digit movement, effects of restraint systems and protective clothing. Second, the computer systems must be streamlined to make them more effective and less costly to operate. Such an increase in efficiency was brought about through the reduction of the computing time for the JANAIR Cockpit Geometry Evaluation program. The time to perform each positional calculation for the man-model was reduced from 45 seconds to 10 seconds. In addition, the modeling efforts must be aimed at providing sub-models or sub-routines which can answer specific questions, for example relating to reach problems, without having to utilize the full-blown model. Looking further downstream, we find systems which will not only provide for evaluation of the design once conceived, but which will be used in actual design process through the use of interactive systems and computer graphics. Finally, one can envision a system whereby through the specification of the system requirements and the mission profiles, a computer-aided function allocation between man and machine is performed, initial workload estimates are made, and preliminary designs are conducted, evaluated, and validated through simulation of the human operator in the full system context. Such a system is currently under long term development by the Naval Air Development Center.

But in order to perfect such computer-aided systems, additional data are required to give the operating basis for the models. As one example, to complete the mathematical model of the man in the CGE system, additional data on the movement of the human are required.

It must be remembered however, that all of the modeling is not going to do any good unless the data are presented in such a fashion that they can be used in the selection and decision process. This process must be, and hopefully will always be, the prerogative of the engineer or scientist involved. One area where recent developments have been very promising is in the development of the integrated approach to the crew system design. Rather than having a series of independent, and sometimes feuding organizations, all the areas involved in the development of crew stations are combined. This approach has shown great promise in a number of government and industry organizations. It provides the opportunity for improved communication and, what is more important, for cross training.

If such improvements can be made at the working level, then they should reflect in the position which can be achieved in the eyes of management. By providing data and demonstrating that an integrated effort is both effective and timely, understandable and useable, we should improve our position and be given the hearing we deserve. By showing that

design can be improved without degrading system performance through rapid and effective evaluation, we should be able to demonstrate the effectiveness of an integrated approach. Most of all, this will be in the form of an educational process for the management of a program. To find ways to achieve this is, after all, one of the objectives of this meeting. And finally, at the customer level, I would like to see earlier definition and specification of the desires and wishes of the procuring agency. Recently, two programs were started by both USAF and the Navy to achieve such an early definition on two advanced systems. Both follow basically the same plan, which can be used as a boilerplate approach to any system development. Let me emphasize that this should be accomplished prior to the initiation of detailed design or even preliminary design. But it will serve to provide sufficient data to assure that the designs can be evaluated and the resultant selection will indeed meet the requirements of the system, thus eliminating the sometimes fantastically expensive engineering changes which are so common in today's environment.

All of this should result in an improvement of the conditions which we provide for the human operator in today's systems. By providing better for him, we should improve his efficiency and thus improve the efficiency of the overall system. But we are not going to achieve such an improvement unless we can show that there are advantages not only to the operator but also to the developer and the procuring agency. In the end, we must show that integrated and advanced approaches will result in savings and thus make the whole approach cost effective. But that is a problem which will be discussed in the next paper.

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DISCUSSION ABSTRACT

• *CDR Lassen, Naval Safety Center:* I agree with your reasoning about why behind-the-line pilots are conservative. But I think the reasons go a little deeper than merely not wanting to learn an entirely new display-control arrangement. Another point is that pilots never know when they might misuse their controls because they revert to what was learned before the cockpit configuration was changed. Pilots are legitimately apprehensive about this possibility.

• *Mr. Hebenstreit, The Boeing Company:* I do agree fully that standardization of cockpits is a vital consideration.

• *Mr. Schmidt, Messerschmitt-Bolkow-Blohm GmbH:* I must agree totally with what you have said about using pilots to assess mockups. We have done crew workload studies together with the British and Italians, and the studies revealed that test pilots are almost invariably prejudiced in favor of planes they have previously flown. If pilots have flown the 104, they prefer 104 cockpits. If pilots have flown Buccaneers, they select a Buccaneer cockpit, and so on. In view of this problem, who is, in your opinion, the optimum test pilot for assessing mockups?

• *Mr. Hebenstreit, The Boeing Company:* This brings us back to our earlier discussion of test pilot education. It dismays me that we have no such thing as a crew station engineer--that is a man who combines knowledge of anthropometry, performance, and design. This is the kind of test pilot we really need, and I think our pilot education program should be revamped to reflect this need. Pilot involvement in the design process is valuable, but before pilots can make significant contributions, they must be properly educated.

• *CAPT Hawkins, KLM Royal Dutch Airlines:* The question of using pilot input in crew system design is very important. While it is essential to take into account the operating capability of the average "line" pilot, he is not the right man to make the critical analysis of a crew station or system. The good "line" pilot can adapt to the deficiencies of the system. He assumes that the tools he has been given are the best available. No pilot who was killed because he misread a three-pointer altimeter ever knew what hit him or why he died, nor would he ever have criticized it in a cockpit evaluation. The good evaluation pilot is one who is normally exposed to the operating environment concerned, who understands the pattern of performance breakdown of the "average" pilot, perhaps through flight instruction experience, and who, when he flies the aircraft sees the cockpit as a collection of deficiencies. When he is asked

by the aircraft manufacturer how he finds the cockpit he does not say "fine," but "where do you want me to start?" There are not many such pilots, but there are enough and interested people in the industry know who and where they are.

• *Mr. Grossman, North American Rockwell:* I would like to add to that statement. The use of the company test pilot to make a subsystem design decision on a part-task basis when he does not know the total control-display system is ludicrous. The customer sending in a pilot to make a decision on one subsystem without knowing all the systems is similarly ludicrous.

• *Mr. Moreland, Army Aviation Systems Command:* Even though I am a human engineer, I would like to make a comment in defense of the pilots. Pilots make good life and death decisions in just about every damn flight or they would not be around. The problem with using pilots to evaluate mockups is that they are usually picked at the last minute and not given the benefit of the design decisions, tradeoffs, alternatives, and considerations that resulted in the particular mockup. If we would give the pilots the facts about two weeks ahead of time--for example, the military specifications, the anthropometric data, the tradeoffs, and other considerations--I bet you would find that they would make as good a decision as you and I in that mockup.

• *Mr. Hebenstreit, The Boeing Company:* I could not agree with you more Steve; that is perfectly true. I do not mean to belittle the contribution of the pilot. I do not believe that we can do the job without his help. I am just saying that we should use a blend of very skilled, highly technically oriented pilots. How we can come up with such a properly proportioned blend, I am not willing to say at this point.

• *Mr. Baumunk, McDonnell-Douglas Corp.:* Backing up this gentlemen, I believe we cockpit designers, engineers, and pilots can do this job and develop the techniques. In fact, I think we already have the techniques, but I believe the fundamental problem is that we do not get users, designers, pilots, and engineers into the design requirement process early enough. And that is why we have made mistakes in the past. You mentioned establishing a rapport between engineers and pilots. I agree that this team concept is essential, and that it must be implemented in the development process as early as when the contract is let. Further, knowledge of the specialty disciplines in cockpit crew design should be available to each team member. And one more point--I think we should use working mockups as early as possible--as crude or sophisticated as the budget permits.

• *LCOL Ravenelle, USAF Aerospace Medical Research Laboratory:* I feel that if you are looking for an innovative answer, you must find an innovative guy to talk to and, I think you will find innovative people in both pilot and designer groups. Similarly, you can find the non-innovative stone wall in either group. You can't blame the pilot for not wanting to see changes. He has a lot of crap thrown at him, so it is not surprising that he is a little cautious about what you want to do to him next.

• *Mr. Hebenstreit, The Boeing Company:* I was not trying to say that conservatism is a bad thing. I think that sometimes we have a tendency to get carried away with all the plethora of beautiful new displays and controls and fail to look for the simplest and most straightforward solutions to problems. Once again, we need a blend of conservativeness and innovativeness to do our job properly. This is what I wanted to imply.

• *LCOL Boren, USAF Aeronautical Systems Division:* I feel we need to use both test pilots and command pilots in mockup testing. But I challenge any of you to give me an example in which the pilot selected to evaluate the mockup will later actually fly the aircraft. What we need at these mockup reviews is the young pilots who will fly the aircraft being built.

I would also like to make a couple of other points about the system in general. I feel we now have more than enough data to make better cockpits. It is for other reasons that we are producing inefficient, possibly deadly, and economically wasteful cockpits. Most of them have been expressed today. But I think another reason is that human factors people are becoming a vanishing breed at the Systems Project Office level. Mr. Godfrey indicated that either they are being promoted, or getting disgusted and leaving. I think most of them are leaving the military services and even some industries to go into easier areas--areas where the parameters are more neatly defined and where there is less frustration. Then, too, I believe that the services overemphasize hardware. Until some group, more specifically the DoD, establishes an office responsible for human factors, I think we will continue to be frustrated and highly ineffective.

WORKSHOP PROCEEDINGS

CHAIRMEN: MR. WOLF J. HEBENSTREIT, THE BOEING COMPANY
MR. KENNETH KENNEDY, USAF AEROSPACE MEDICAL RESEARCH LABORATORY

WORKSHOP DISCUSSANTS

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MR. EUGENE FARBER, Ford Motor Company
MR. ANTHONY A. FEWING, The Boeing Company
MR. HAROLD FRIEDMAN, Naval Missile Center
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MR. JEFFREY D. GROSSMAN, Naval Weapons Center
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MR. HUGH T. WEBSTER, Weber Aircraft Company
MR. GLENN H. WILLIAMS, Northrop Corp.

ABSTRACTS OF WORKSHOP PAPERS

A TECHNIQUE FOR ASSESSING OPERABILITY/EFFECTIVENESS OF CONTROL-DISPLAY SYSTEMS

James J. Belcher
Litton Systems, Inc.

In the past, both time-line analysis and dynamic-simulation techniques have been used to evaluate the overall effectiveness of a crew station design, but only after the system is well along in the development cycle. This paper describes a computerized technique for evaluating the relative operator load within a realistic mission context. The technique is called the time-based load analysis (TBLA). The advantage of this approach is that a feedback on the control/display design effectiveness is possible very early in the development cycle. If changes are required, it is much easier to effect them early in the design process rather than when the program is reaching its maturity. In summary, the TBLA:

- Provides assessment of operator/avionic system mechanization--short of simulation or actual flight.
- Provides a diagnostic technique for assessing overall crew/system effectiveness.
- Isolates operator overload situations.
- Allows feedback into crew station layout for correction purposes.
- Puts the entire mission into an operating context.
- Provides guidance on test and evaluation areas.
- Evaluates the impact of contingencies on operator performance.

COCKPIT GEOMETRY WITH NONADJUSTABLE SEATS

Harry W. Holder
USAF Aeronautical Systems Division

Past and present crew station geometry has required an adjustable crew seat to allow the full range of pilots to position themselves on a horizontal vision line to insure optimum external vision.

This paper presents a new concept in cockpit geometry wherein seat adjustment is no longer required. This is achieved by providing the required downward vision angle from the design eye position of the small pilot when seated on a fixed (nonadjustable) seat and providing the required upward vision angles from the design eye position of the large pilot seated in the same seat.

The benefits of this concept are not limited to external vision, but also result in effective control location and actuation, increased internal vision, accessibility of controls located on side consoles and instrument panels, reduced rudder pedal adjustments, reduced seat structure weight, increased survival kit volume, increased throttle, and rudder pedal/brake actuation.

CREW STATION DESIGN USING COMPUTER GRAPHICS

Edward O. Roberts
USAF Flight Dynamics Laboratory

This paper gives a brief description of a computer program written by the Air Force Flight Dynamics Laboratory to generate external vision plots for an aircraft cockpit. The program involves the use of a Control Data Corporation Digigraphics Display console which allows the designer to see a visibility plot on a CRT screen and to interact with the computer to change the design eye point or the size and/or position of the "windows." An example is presented which illustrates a specific application of the program.

FRONTIERS IN WORKSPACE APPLICATIONS OF ANTHROPOMETRY

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Rockwell

K. H. E. Kroemer
Aerospace Medical
Research Laboratory

W. G. Thomson
Convair
General Dynamics

An underlying structure of procedures and techniques applicable to all workspace designs is presented in flow-chart form. Needs for future developments in differing types of anthropometric data, improved techniques of body measurement, and application synthesis and analysis techniques are described for selected operations in the procedure.

Illustrations of examples of current and promising approaches are presented, primarily from spacecraft and aircraft design studies. These include simplified methods of presenting design criteria for bivariate data, procedures for population synthesis (estimation from minimal data), special measurement devices and design aids, considerations of accelogravitational forces, mobility notation, key design points, and computer applications. Generality of concept in approaches is stressed, and interaction with the requirements of other disciplines is identified.

RESULTS FROM A COMPUTERIZED CREW STATION GEOMETRY EVALUATION METHOD

Patrick W. Ryan
The Boeing Company

The Cockpit Geometry Evaluation (CGE) program is designed to eliminate some of the inherent limitations of present geometry evaluation techniques such as biases of the evaluator, untimely responsiveness, and high cost. A computer program system (CGECPS) has been developed and includes a dynamic mathematical man-model (BOEMAN) capable of simulating the movement paths of any-sized seated operator. Consequently, reach infeasibilities, visual interferences, physical interferences, and performance indicators can be ascertained for any crew station early in the design process. In addition, the system includes computer graphic displays of the geometry being evaluated and the man-model movements, as well as the option to subject the design to compliance checks against geometry oriented Military Standards and Specifications.

A "levels of evaluation" concept has also been developed and the CGECPS has been subjected to initial validation on the A-7E crew station. The results were highly encouraging. The extension of the CGECPS to other crew system problems has also been investigated. While many areas are promising, the evidence would indicate that several components of the CGECPS are directly applicable to computer aided design with interactive graphics--an area that the Crew Systems Technology has been remiss in developing.

HIGH ACCELERATION COCKPIT DESIGN

Dennis W. Schroll
USAF Aeronautical Systems Division

A configuration where the pilot is positioned with seat back at 25° aft of the vertical and legs elevated to the level of his buttocks, and with a seat back reclinable to 65° aft of the vertical for the high-g condition was chosen as the most promising to investigate for utilization in a high acceleration cockpit. To construct a final mockup of the seat configuration, tests were run to determine the mean hip pivot point of the seat back and the medial elbow locus so that reclining armrests could be constructed. The seat, which reclined by the use of actuators, was placed in a mockup somewhat representative of the F-15. Tests were conducted to establish crew station requirements, and these are discussed in this article. In conclusion, the configuration investigated was considered very functional for use in a high acceleration cockpit. Major problem areas which require further investigation are controls and displays, crew escape, and the unknown involved in the high-g environments as related to the seat back recline system.

WORKSHOP HIGHLIGHTS

GUIDANCE COMMITTEE COMMENTS

• *Mr. Hebenstreit, The Boeing Company:* The basic aim of this workshop is to try to answer some of the questions we have presented in the overview papers or any other questions that come to light during this workshop. Our objective is to present some concrete conclusions in the final report on this workshop. I am not going to restrict the workshop to crew station geometry, because we should also consider other related problems such as vision, crew station arrangement, evaluation, and design. Ken Kennedy and I presented our views in our respective overview papers. Now I am going to ask the other members of the steering committee and Tony Fewing to give us their ideas on the most important problems.

• *Mr. Lazo, Naval Air Development Center:* Geometry and workspace arrangement problems can be approached in two ways. First, we can tackle specific crew station problems confronting us. The other approach, which most participants of this conference have been advocating, is to consider our problems within the context of the total system. What concerns me, however, is how can we actually do this? Over the years, we have become less innovative because we have been increasingly restricted by pre-existing design concepts. For example, the F-14 has 64 control panels and 33 of them are GFE. The remaining panels, which might have represented the advanced state of the art, had to be compromised to be compatible with existing equipment. Further, aircraft production is reaching a stage where we are not familiar, when designing, with some of the components the operator will be using--only later is this information available. I simply do not know how we can integrate systems performance and human performance without this information.

I would like to address some questions to this workshop. First, what constitutes good crew station geometry and workspace arrangement? It is very difficult to find an answer to this question. What are the problems? I think everybody acknowledges that aircrew accommodation encompasses such factors as crew performance, safe emergency ingress and egress, and operator psychological and physiological well being. These so-called comfort parameters have been described in the past, but not quantitatively. I think we should try to quantify these parameters and establish specific criteria for them. Any number of documents state that the crew system should be designed for effective and safe operation, but what constitutes effective and safe operation? I think that effective operation can be related to workspace envelopes, but what are these workspace envelopes? If the vehicle is to operate effectively, particularly under stress, we all acknowledge that certain reach capabilities must be provided. But the capability of individual operators differs. We cannot state with any degree of confidence what controls should be placed within the reach capability of the population when the shoulder is immobilized under high g conditions. Effective methods and techniques for specifying these aircrew station objectives and criteria are not available.

I would like to make the following suggestions. First, we should specifically outline the objectives and criteria of good crew station geometry. Since we are dealing with the human, body dimensions and their interrelations should be taken into account in aircrew station design to achieve effective operator performance, safety, and comfort. We should be in a position to tell the designer how to use these body parametrics.

Second, we should develop effective and timely design methods and furthermore, we should develop techniques to evaluate whether our design methods are actually producing crew stations that meet the criteria of good crew station geometry.

Third, we need better communications between the various disciplines and a clearer delineation of responsibility for scheduling for the various disciplines. The buck is very often passed from life support to escape to displays and controls.

Finally, I think we should determine to what extent crew station geometry and/or the crew station arrangement should be standardized.

So I think we have a twofold problem. How are we going to shift the design cycle today and how can we implement it in the future? This might be accomplished by establishing management authority to recognize the problems

and pass them down to the developers, or by encouraging greater interdisciplinary cooperation at the working level without directives.

• *Mr. Holder, USAF Aeronautical Systems Division:* It goes without saying that the cockpit or crew station is the most complex area in the aircraft. We all know that everything in the aircraft ends up in the cockpit through a switch, lever, display, etc. It is getting to the point where everything is a problem in crew stations these days.

The major problem facing me in crew station evaluation is not the maze or quantity of the instruments but the *size* of today's instruments. I am very concerned about where we are going to put these new instruments on the panel. Plasma indicators for engine outlets may be critical, but if they are going to displace basic flight instruments we have a real problem. I do not know how you integrate something like this into a crew station. We have problems trying to find an optimal location for gunsight installations and head-up displays without disrupting an instrument panel. Some instrument panels, in fact, are completely obliterated in the center by gunsight installations. You wind up with basic flight instruments split up in two groups. Instead of a T arrangement we have two parallel rows of instruments on either side of the gunsight.

Another problem is standardization. Years ago our objective was to get our cockpits exactly the same--to standardize knob shapes and the location of critical controls. With new advanced systems coming up, it is anybody's guess as to what the controls will look like and where they are going to be located.

I think we should also examine the question of audio tones. Although the Air Force strongly supported them at first, we later found that if you exceed five tones a pilot has difficulty remembering what a particular tone is associated with, especially if he is not exposed to the tones on a day-to-day basis. Therefore, we are now leaning toward the verbal warning system. Data requirements are coming in from contractors.

As most of you know, we have an aircrew station standardization panel that is dealing with a lot of these questions today. But I would certainly like this group to consider how we can formulate good data requirements, good standards, good specifications, and so forth. There are so many problems it is overwhelming.

I recall two of the questions that were on the announcement of this conference. One, what to your knowledge has had the greatest impact on crew station design? I had to say bigger instruments, bigger CRTs, and bigger gunsights. Second, what do you anticipate in the future for crew stations? My answer was bigger CRTs, bigger gunsights, and bigger instruments.

• *Mr. Susser, Lockheed Aircraft Company:* I would like to discuss some of the problems in commercial programs that have yet to be solved. A commercial program is very different from a military program. In the military, you usually build one airplane for several customers. Granted there are derivatives of that airplane, but there are very few basic differences. However, in a commercial program you build a different airplane for as many customers as you have. It is the same basic body shell, but aside from that there are many differences--completely different navigational systems, for instance. We wrote a model specification for the L-1011 at the beginning of the program, and as each new customer was signed up we wrote a new specification for that particular customer. So nobody really bought the basic airplane.

There are no specifications as such for crew station or cockpit design, but we have to adhere to FAA regulations in designing the basic airplane. In order to start with some standard, we went to SAE documents and whatever military documents we felt applied to a particular design problem. At Lockheed we wrote a flight station controls and displays standardization criteria document, which to a lesser degree also took into account such things as instrument layout and cockpit geometry. This document standardized every piece of hardware in that airplane--crew seats, personal equipment, indicators, switches, etc.--so that even with the myriad of subcontractors required, when the hardware wound up in the airplane, everything looked like it came out of one box. In fact, the L-1011 looks like it was designed by one designer and built by one manufacturer. All the instrumentation has the same requirements for lighting and scale makeup, regardless of who actually built the instrument. Power switches are the same size and look the same. The point I am making is that everything the crew sees and touches looks the same.

We are very different from the military in the sense that we get a shell from the advanced design group that meets speed, altitude, and operating-cost requirements and then we have to equip it with everything else that is required to fly the airplane. The aerodynamics people beat on us, the thermal dynamics people beat on us, the structures people beat on us, and by the time we are through we are lucky if we have something left to allow the crew to perform their jobs safely and efficiently.

Another problem in commercial programs

is that you build an airplane to satisfy commercial airline requirements and then the military comes along and wants the same airplane. Now you have to use military specifications that were not considered in the basic aircraft design. This is a basic problem, because even though a lot of our equipment is designed and built to military specifications a lot of it is not and does not have to be, because the airlines are not going to spend money if they do not have to.

Another problem is that in a multi-place large airplane, we have a third crew member--the flight engineer--whose role must be considered. He is a professional with some airlines, but just a pilot waiting to move up the line with other airlines. The role of the flight engineer heavily influences the design of the flight deck. He probably uses as much hardware as the pilot and copilot.

Another big problem is warning lights. Airline pilots tell us that they do not want red warning lights to alert them to problems they cannot solve. Where remedial action is not possible, they want the warning lights to be amber or blue--anything but red.

On the plus side in commercial programs, we are not involved in pressure suits and the myriad of personal equipment that the military must consider. But we still have to consider the personal equipment that aircraft captains carry aboard.

• *Mr. Roebuck, North American Rockwell:* I have the best and worst of all possible worlds in the space business. Basically, I think we have all the military and commercial problems and to that we add another dimension, which is the change in assilo-gravitational forces. That means anything that changes the vector of load on the pilot, such as launching in the vertical attitude and landing in a horizontal attitude and going from a three to five g load to a zero g environment in orbit. We also have the full pressure suit considerations. We are trying to approach a shirt-sleeve environment but we cannot just pull an oxygen mask out and put it on, because it is a long way down. So we have to consider the decompression problem, which has a big impact on the design of the vehicle. We are also concerned with the orientation of the vehicle during launches. We have some changes in orientation as it goes up right now, we may have as much as a 13° change in attitude from a vertical to a pitch-up condition. So this is a new ballgame as far as most airplanes are concerned.

One of my pet peeves is that when I begin to lay out a crew compartment based upon fixed-eye position, I can find very little data that tell me what I can reach and how much clearance I need based on that eye position and a fixed seat reference point. I feel that is an unsatisfactory state of the art. After 20 years we should be able to better define our reach envelope and clearance envelopes. By the way, those envelopes are really different when you have a pressure suit on.

I think we need a lot more attention to dimensions in terms of the actual work position of the man in the crew compartment. Also I think we need more rapid techniques for evaluating the crew compartment design. I think the computer program concepts are good, not only because they can react fast, but also because they force us to examine the dimensions of the body in a kinematic sense. That is, to identify the location of the joints, the links, and so on, with respect to the clearance requirements.

I think that more attention should be given to soft mockup techniques and their economics in the crew compartment design process. In our program we are not able to compare the costs of how we did it with the costs of how we should do it. In that area I think we should concern ourselves with such fine details as what percentile we should design to and what you get for it in terms of dollars. That requires the collection of data concerning the correlations between the various body dimensions. In my opinion, there is not enough of that kind of data.

• *Mr. Fewing, The Boeing Company:* I think the crew station designer has a massive integration problem on his hands. He is not an expert in any of the supplementary fields that contribute to the crew station, but he still has to integrate data from all the fields in a way that will satisfy management, stay within cost limitations, and satisfy the customer as well. He knows right from the start he cannot do that because if he asks five or ten people to evaluate his crew station he will get ten different evaluations. The best he can achieve is a good compromise that does not satisfy everyone but still meets the mission requirements. On top of that he must design a crew station to meet the requirements of the mission, but these requirements are sometimes the hardest part to pinpoint. The designer will be told to design a crew station for a fighter or bomber, but often is not told early enough what actual weapon will be used And without that information on day one, he can't start. Add to that, all the inputs he will receive about life support, displays and controls, general anthropometry, and location of the critical elements. If he cannot specifically identify these requirements before the wind tunnel testing is completed, he is dead. The moment the wind tunnel testing is completed and the body shape is fixed, he cannot change the canopy lines, cannot get any additional width, and can be faced quite often

with inadequate depth underneath the cockpit panels. Then he is confronted with the problem of wanting to get all the instruments and all the controls forward of the seat reference point, wanting to place everything to avoid a backhanded motion, not wanting to introduce any actions that will result in pilot disorientation, etc. And yet the structures people are saying that he has plenty of room, why not go back to the bulkhead with the equipment? So the designer is unpopular with the structures people, because they think he is not utilizing all the space that they have made available. But he cannot utilize this space without ending up with a bad design that would create unsurmountable problems for the pilot.

I feel that in general we have enough data right now to lay out a crew station in relationship to the eye reference point, to the seat reference point, and the reach envelope. I really do not think we have a problem in that area. I was surprised when someone said that we do not have data on the pressure suit reach envelope--several reports define the restrictions of a particular pressure suit. I think the data are there, but quite often it is difficult to find them in the 45 days you have to respond to an RFP. I do not think that many additional anthropometric data are needed. Further, I believe that anthropometric data in the bivariate form are the most useful for laying out the crew station.

• *Mr. Hebenstreit, The Boeing Company:* In summary, it appears to me that we are talking about three major, closely connected, areas. First, we seem to need data, basic data about the human body in terms of operator performance. So, I think we should define what data we need and in what form. A related problem is the difficulty of getting the appropriate specifications and standards into the design cycle early enough and in an applicable form so that the designer can actually use them when he sits down at the board. The other big problem that was brought out seems to be evaluation of designs. This will go on throughout the design cycle but I have written it down as a post-design task since something must be designed before it can be evaluated.

RESEARCH REQUIREMENTS

• *Mr. Lazo, Naval Air Development Center:* I would like to comment on our data requirements. I agree that we have a lot of data, but most of our information is disorganized, difficult to find, and difficult to apply to the conceptual design of a crew station. Several specific research needs come to mind that are directly applicable to crew station geometry.

What is horizontal visual angle? Everyone in our country defines it in terms of the fuselage reference line. The Europeans define the horizontal visual line as being parallel to the mean chord line, regardless of the aircraft's angle of incidence or angle of attack.

How does the neutral seat reference point relate to the body position? Our escape system people have no way of predicting body position from the neutral seat reference point.

We need objective data with which to identify the crew's external vision requirements as a function of mission profile. I am merely talking about minimal requirements. The minimum vision requirements described in our reference documents are predicated on the window area we have been able to provide in existing aircraft of various types--not on the window area pilots may actually need. This is not a rational basis for defining minimum vision requirements.

The HIAD and the present military standards require the designer to develop a cockpit that is optimal for a 50th percentile pilot sitting in a neutral seat reference position. The standards require that the body be moved for the extremes of the population around this design point. A recent military standard, MIL STD 1333, essentially did away with this approach. This document, coordinated by all three services, allows the contractor wide latitude in crew station geometry. It specifies what capabilities we want for the population in terms of reach, escape systems, safety, and so on, but it does not specify how this is to be achieved. Two Navy aircraft have been built using this approach. The geometry in these aircraft has no resemblance to the military standards. These two aircraft have essentially satisfied 95 percent of the aircrew population. However, this document makes it very difficult and time consuming to determine whether the drawings submitted in proposals do indeed provide the capabilities that were specified. We need data and methods for making these types of evaluations. We need additional anthropometric data and we need methods to apply these data in designing crew stations. There are a lot of data available in the design application area, but how do we apply these data?

We should be addressing the problem of time sharing. If we do not conduct this type of research, we will not be able to tell our subsystems people what displays should be time shared. Studies should be conducted to identify the functions that are never performed at the same time. These data are required to establish a basis for time sharing of displays and multiplexing of controls.

We are going to computer-aided

operations, so we need to know the types of controls that are compatible with computers. There are also problems associated with the use of switches. When is it more appropriate to use a lighted switch than a standard toggle switch?

These are some of the data we need to do our job better. Management must be made aware of our needs and convinced that they should sponsor the research required to generate these data.

• *Mr. Grossman, North American Rockwell:* We do not have enough conceptual studies prior to preliminary design. We do not have the necessary knowledge or manpower to realistically define the display and control systems we need in an airplane. We do not have any realistic method for integrating the systems design, the control/display design, and the aircraft manufacturing schedules. We do not have any quantitative criteria that will tell us the effect on the total system of the addition of a new display or control. These are some of the data we must have before we can propose a realistic approach to management.

Design based purely on the expertise of pilots, copilots, test pilots, Air Force review boards, and Naval review boards is not adequate. The average operational pilot who is going to use the equipment in the field is never used during the design and evaluation process. A man becomes a test pilot because he has the capacity and initiative to overcome all of the obstacles in his field. So, what is good for the test pilot is not necessarily good for the man in the field.

Do we need all of the specifications currently in use to design a crew station? I am not so sure that all the specifications are really needed. The manufacturer should be given the funding and responsibility to define the crew station needed to meet the customer's requirements.

We do not perform our task analysis, our link analysis, our contingency task analysis, our fault-free analysis, and so on early enough to have any effect on the design.

We do not use systems integration. We use pilots to make a subsystem design decision when they know little or nothing about the *associated* subsystems. I think it is impossible to make an intelligent decision about the design of a subsystem without a thorough knowledge of the entire system.

Does a crew compartment really have to look good to be effective and usable? I am not referring to esthetics, I am referring to design commonality.

These are some of the issues that I think we must address before we are ready to talk with people at a higher managerial level.

• *Mr. Ryan, The Boeing Company:* I think we need more bivariate data for the human body. Although multivariate data may eventually be useful, I think it is unduly complicated for the designer at present. For example we have little data on spine motion, an important and very difficult problem. People from the University of Michigan are presently doing some work on spine motion, so perhaps this deficiency will be eliminated soon. Although Wright-Patterson has worked on pressure suits a great deal, we need more data about the dimension of pilots when wearing a pressure suit. Another important area concerns the effect of high g loading on the body. I would be astounded if the model we are developing at Boeing did not have to have many new assumptions when we consider high g environment.

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* I think we can all sit here and enumerate very important problems that very few people would challenge. But we do not live in a totalitarian state. We have ten or 15 large aircraft companies and thousands of suppliers to the aircraft companies. These companies are primarily manufacturing companies. Although in recent years they are increasing their research, they are not primarily research companies. Present research is fragmented and unorganized. An organization must be set up to coordinate the necessary research for any particular field. Any research effort that is so important to the Defense Department must be coordinated if it is going to work. I think this is something we should be shooting at also.

ADEQUACY OF SEAT ADJUSTMENT

• *LCDR Gregoire, Naval Air Test Center:* Many of the problems in seeing through head-up displays and gunsights and in reaching aircraft controls could be eliminated, I believe, by providing the pilot with more seat adjustment. The seats in most military aircraft are tied to an ejection rail that inclines toward the rear of the aircraft. Therefore, the pilot is necessarily moved aft as he adjusts his seat upward. Short pilots must adjust the seat upward to achieve adequate visibility out of the cockpit. Yet when they do so, they are moved further away from the controls--in some cases, entirely out of reacn of emergency controls. I recently surveyed ten first-line Navy aircraft and found that a sizable proportion of the pilot population could not reach the emergency controls. So, I would like to propose that aircraft be equipped with seats that can be adjusted up and down, fore and aft, and that also can be tilted. Furthermore, I propose that the range

of vertical adjustment be greater than the approximately five inches available in most contemporary aircraft.

• *Mr. Lazo, Naval Air Development Center:* This has been done, so it is technologically feasible. Fore and aft adjustment of the seat was provided in the interim 111. However, you do have the problem of use, particularly for ejection.

• *LCDR Gregoire, Naval Air Test Center:* One other point. The F-106 has a seat that can be tilted 10° or 15°. This tilt capability, according to a survey I conducted, solved most of the reach problems that are present in other aircraft.

• *Mr. Hebenstreit, The Boeing Company:* Could current aircraft be retrofitted with the type of seats you are proposing?

• *LCDR Gregoire, Naval Air Test Center:* I think the types of seats I am proposing are within the present state of the art and that it would be possible to install them in both current and future aircraft.

• *Mr. Lazo, Naval Air Development Center:* We want the capability for placing each pilot's eye in the design eye position, regardless of his size. So, this is what we should ask for rather than recommending a specific technique for accomplishing this objective.

• *LCDR Gregoire, Naval Air Test Center:* Another point is that pilots do not fly an entire mission with the seat positioned in the same place. When making a carrier landing, pilots adjust their seat upward because they want to see as far over the nose as possible. When going in on a strafing run, a pilot wants his head down so he can see through the gunsight so that he makes less of a target for the enemy, and in this case he adjusts the seat down.

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* To complicate this whole picture, we have found that individual pilots differ as to what position they prefer for any given flight segment. Some pilots put the seat all the way up for takeoff and others put the seat all the way down. So there does not seem to be any fixed pattern as to the position the pilots assume in the cockpit at any one time during the flight.

Is there any way the designer can prevent the pilot from assuming a bad position in the cockpit? For example, a short pilot may run the seat all the way up during a landing and be incapable of exerting sufficient force on the rudder pedals from that position.

• *Mr. Meinhardt, General Dynamics/Convair:* I think that too much adjustment in the seat can cause problems, because the other controls are not adjustable. When the little man gets too high he may not be able to reach full throttle. Furthermore, the escape people do not like this because it increases the size of the escape envelope and imposes requirements for returning the seat to a preset position.

• *LCDR Gregoire, Naval Air Test Center:* Although increased seat adjustment will cause engineering problems and will undoubtedly cost more money, I think the decrease in accidents and increase in pilot performance will more than justify this change.

• *Mr. Hebenstreit, The Boeing Company:* Why don't you have specifications that call for more seat adjustment?

• *LCDR Gregoire, Naval Air Test Center:* I think this committee should recommend a specification that calls for more seat adjustment and adjustment in various planes.

• *Mr. Holder, USAF Aeronautical Systems Division:* I would like to point out that at one time in the Air Force we did have a seat specification that called for a forward and up diagonal adjustment, which worked beautifully on the board and tested out perfectly with mannequins. Unfortunately, our people just were not built that way. You get a guy with a short torso and long arms and you have got problems. So we had to delete that specification.

THE FLY-BEFORE-BUY CONCEPT

• *Mr. Fewing, The Boeing Company:* Every time we get an RFP, the first two or three pages list certain relevant specifications, guidebooks, etc., that you are to conform to. So right from the start, they tell you to be innovative, but at the same time remind you to comply with the specifications and guidelines.

• *Mr. Holder, USAF Aeronautical Systems Division:* Your problems with standards and specifications may soon be over. The Air Force is entering into a program that will not limit the contractor with military standards, military specifications, or guidance documents. It uses a fly-before-you-buy concept in which two contractors will be awarded a contract to build prototypes to fly off competitively. Decisions will be made on the basis of aircraft performance data--i.e., speed, range, altitudes--and human performance will not determine who will get the contract. I hope you realize what impact this has. I do not care how many standards we come up with, how qualified they are, or how many data we provide, the aircraft's performance will determine who will build it. The crew station will receive little or no consideration when this

decision is made.

• *Mr. Senderoff, The Boeing Company:* But doesn't that program also say that "thou" shall have a human factors program, a systems safety program, a survivability program, a reliability program, a maintainability program, and that the customer is going to assess all those aspects in deciding who will win the contract?

• *Mr. Holder, USAF Aeronautical Systems Division:* This is true, but the services are going to have to rely on the contractors to do this. If we cannot specify a geometry, a layout, an instrument arrangement, an ejection seat, an escape system, or what have you, we are still going to have to rely on the contractor. If for example "Ace Engineering" gets in the contest and builds a cockpit with a rear-facing seat, we have nothing to say about this. If it wins the contest on the basis of superior performance, we are stuck with a rear-facing seat. You and I know that it is going to be extremely difficult to justify any high-cost retrofits at this stage.

• *Mr. Fewing, The Boeing Company:* If you get good aircraft performance with a very narrow cockpit, then after the flyoff, you are stuck with that narrow cockpit.

SELLING MANAGEMENT

• *Mr. Hebenstreit, The Boeing Company:* We have talked about certain needs and certain things that have to be done. Does anyone have any good ideas about how to make it obvious to the upper eschelons of both industry and government that these problems are important and must be solved?

• *LCDR Gregoire, Naval Air Test Center:* Draw up a specification.

• *Mr. Hebenstreit, The Boeing Company:* That is one way that the industry can beg the question. However, I do not think that is the solution to the problem.

• *Mr. Susser, Lockheed Aircraft Company:* Make it a part of the RFP.

• *Mr. Hebenstreit, The Boeing Company:* Does it behoove us to put the onus of this whole problem squarely on the government people? I somehow do not think it is quite fair to tell the government to give us all the information we need to design the crew station.

• *Mr. Susser, Lockheed Aircraft Company:* Yes, but if you make it a requirement long enough, over a period of time it will become normal, and it will be used without imposing a requirement. I think we should strive for a way to show that by doing certain things at different times from the times we now do them it will reduce costs and result in a safer crew station. Commercial customers buy airplanes on the basis of operating costs per seat mile. If you can show management, in dollars and cents, that they are going to be ahead of the game by doing it this way, then they are going to do it.

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* Being able to show that either additional money is not necessary or that, in fact you save money, is probably going to be quite difficult. But in the military more than in commercial aircraft we have other valid arguments. That is, we can cite cases where because a certain thing was not done, an extremely dangerous situation was created. We can certainly show piles and piles of negative information.

• *Mr. Schmidt, Messerschmitt-Bolkow-Blohm GmbH:* Are any investigations of aircraft accidents caused by bad cockpit design being made? Could we cite those investigations to convince the government to alter specifications and standards in the right manner?

• *Mr. Hebenstreit, The Boeing Company:* I also wonder why this information has not been used for this purpose.

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* For years, whenever there has been an air-to-air collision involving commercial aircraft, there have been, for instance, visibility studies tracing the relative position of one aircraft to the other. That is, a historical analysis leading up to the point of impact was made. So, they have very detailed analyses of some accidents, especially those involving air-to-air collision.

• *Mr. Lazo, Naval Air Development Center:* I think that over the past 25 years nobody would disagree about the deficiencies in crew station design and their consequential operational deficiencies. I think maybe one of the problems is that if I have a deficiency associated with navigational gear, I go to one man. But, if I have a crew station problem, in industry or in the procurement management agency, I can't go to any one man responsible for crew station design.

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* But in addition to that, our complaints come to the authorities piecemeal and from all different directions. This should be organized. Perhaps this problem could be solved through this conference.

• *Mr. Hebenstreit, The Boeing Company:* I think there is one thing that we should admit and that is that engineering changes are not altogether unprofitable. People have

submitted a design idea with the full intention of later introducing a change. Although I am not accusing anyone of deliberately designing something so that he can afterwards make a buck on an engineering change, nevertheless each engineering change does make a profit. I think a method that would eliminate engineering changes would undoubtedly be highly cost effective, for the customer at least. I believe that in recent procurements government is imposing stronger restrictions on the contractor to stay within the cost and design of his proposal. But it is still very difficult to convince management to put forth 50 or 100 thousand dollars needed for these preliminary studies.

• *Mr. Senderoff, The Boeing Company:* Isn't that the answer? You would not submit a proposal on an airplane without doing wind tunnel tests first. So, why can't you have a requirement that certain reasonably complete human factors analyses, crew systems analyses, and so on be submitted as part of the RFP response? In other words, submit analytical data that justify your crew station design.

• *Mr. Hebenstreit, The Boeing Company:* The problem is that there is typically never enough time to perform the required analyses. So, I think you must either persuade industry management that certain things have to be done before you receive the RFP or you get the government to realize that some of this research and analyses must be done first and, of course, to provide the funding required. Incidentally, we are working on two such systems at present, and the analyses that I am referring to are not very expensive. If government did support this type of (pre-RFP) research, a crew systems specification could be attached to the RFP. Then the designer would not be required to dig through stacks and stacks of paper looking for one needed data point.

• *Mr. Susser, Lockheed Aircraft Company:* Let's face it, that is not the way contracts are awarded. Military contracts are awarded to the least expensive supplier. After the RFP is submitted, you people in the contract agencies review it, and the contract is awarded to the least expensive supplier. Only then do you say, "Now that you have won the contract let's get down to business and design this vehicle." I think the procuring agency should be more involved with the contractor all through the design process.

• *Mr. Lazo, Naval Air Development Center:* I do not think there has been one crew station design situation where the crew station designer has said, "This is the envelope we need," and then he was given the envelope. Why? Because he does not have enough information. Information about crew station requirements comes in too late, after the configuration (aircraft) has been frozen.

• *Mr. Susser, Lockheed Aircraft Company:* Let me make one point in the area of flight safety. I know for a fact that the Inspector General of the Office of Flight Safety has compiled enough paper work to fill this whole building in the investigation of accidents. There has not been a commercial company in the country that has not been involved in litigation because of an accident involving the death of a passenger. At Lockheed we had a great amount of information about past litigations, both ours and those of other companies, and when we built the 1011 those court cases and the associated design deficiencies were thrown on the table and we were told that the deficiencies identified during the court litigation would not show up in this airplane. Perhaps the military should do something similar. That is, they should put all this flight safety information together in an easily retrievable form and use this information to identify deficiencies and insist that these types of deficiencies not show up in future aircraft.

• *Mr. Roebuck, North American Rockwell:* What we are really offering, as I see it, is a kind of insurance in which we say if you put so many dollars and so many kinds of skills into the program we will come up with a safe, cost-effective system. The only problem is that usually it is difficult to pin responsibility on the company that is actually responsible for the design deficiency. Another problem is that we do not have the information that will show the relationship between cost of litigation on the one hand with the cost of good design on the other.

• *Mr. Lazo, Naval Air Development Center:* I think that everyone who designs for man-operated equipment assumes a responsibility for satisfying human needs and safety.

• *Mr. Roebuck, North American Rockwell:* But it is only a moral responsibility in most cases.

• *Mr. Lazo, Naval Air Development Center:* Even though there have been documents that attempted to pinpoint responsibility, you are correct in saying that the responsibility for safe design remains a moral one. Maybe it is our responsibility to identify exactly who is to be responsible for crew design problems. I do not know who to point to when I find a glaring deficiency. We build aircraft in which the pilot cannot see the carrier during carrier landings. Who is responsible?

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* In this day of rapid change we are going to eventually see legal cases brought against manufacturers and human engineers by the military.

• *Mr. Hebenstreit, The Boeing Company:* I

think some of the glaring problems can be avoided. I can foresee a time in the not too distant future when instead of submitting drawings, we submit a computer tape which would be fed into an evaluative computer program. That would be one way you could avoid glaring errors.

• *Mr. Grossman, North American Rockwell:* I propose that this group recommend that a government funded study be made to document the cost attributed to the many factors in crew station design. This study should start with a search of the present literature, and proceed to an evaluation of the data compiled during the literature search. The military has so much data available on the causes of accidents, down time, etc., that if we got all those data together, analyzed the information, and then validated it through some flying method, we could come up with what we really need to design a crew station. Even at that we are never going to get a crew station that is designed exactly the way we want it, but we can approach a level that we are not attaining today.

• *Mr. Holder, USAF Aeronautical Systems Division:* I agree that a good investigation along these lines would be beneficial to everyone. However, we must keep certain things in mind. I keep getting accident descriptions concerning cases in which a pilot has forgotten to put his gear down. This has been attributed to bad design, a break in habit on approach, and so on. Now, how do you cover something like this? We can simply attribute it to pilot error and say that we lost an airplane because the pilot forgot to put his gear down but our problem is to define how much we would save with a good crew station design.

• *Mr. Grossman, North American Rockwell:* What I am trying to say is that if we can at least find out what a lousy design costs us, we have some ammunition to support our case with management and the customer. Coming up with dollars and cents proof is the only way I can think of to show not only your manager but also your customer what he is getting for his money.

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* A very large percentage of our remarks so far have been directed toward the design of a new aircraft cockpit. I would like to go on record as saying that the same requirements imposed on new design continue to be utilized during the entire life of the aircraft. I venture to say that a majority of accidents that result from poor cockpit design come about as a result of retrofits, or the addition of other equipment into the cockpit *after* the service has accepted the aircraft. People add things such as seats without sufficient investigation and they totally mess up the geometry of the cockpit. They add other equipment that protrudes into the ejection envelope which constitutes a safety hazard. So, I would like to put in a very strong plea for assessing this aspect of cockpit geometry.

• *Mr. Fewing, The Boeing Company:* We have been discussing the evaluation of a cockpit design in terms of dollars and cents. I think it is absolutely necessary that performance be brought into the picture. We can build cockpits for less money, but unless you relate this to the performance of the airplane we are going to be in big trouble with both industry management and the customer.

WORKSHOP SUMMARY

Mr. Hebenstreit, The Boeing Company: Ladies and gentlemen, the workshop on crew station geometry and workplace layout was chaired jointly by myself and Ken Kennedy. We were assisted by the Guidance Committee consisting of Mr. Holder from Wright-Patterson Air Force Base, Mr. Lazo from the Naval Air Development Center, Mr. Susser from Lockheed, and Mr. Roebuck from North American Rockwell.

The workshop focused on three basic issues: a definition of the major problems; a definition of potential solutions to the problems; and a definition of ways to persuade management that our proposed solutions are desirable. Our basic problem, which has been with us for a long time, is trying to design from the inside out instead of from the outside in. In other words, put the man in the system before the system is defined, not afterwards, so that he will not get stuffed into whatever little space is left over.

There are three major problem areas. First of all, our main problem seems to arise from the current timing practices of government and industry. It is common knowledge that we seldom get the required crew systems design data soon enough to influence the design of the airframe. Once a body design has been through wind tunnel testing, there will be no subsequent changes to it. In other words, the crew station design decisions have to be made before the body lines are finally determined. To solve the problem of timing, we recommend that government and industry provide a longer lead-time for crew station design. Analytical work should be started, and perhaps completed, even before an RFP arrives. Although this process would cost money, it is perfectly feasible and would be cost effective in terms of the benefits accrued from it. We would finally be entering the process early enough to prepare properly, and we would have the timely arrival of data the designer needs to lay out his crew station.

Another major and perennial problem in crew station design has been the inability to approach management because the many people involved are divided into separate groups. We need to encourage government and industry to look at the crew system as a single entity. I would suggest consolidating anyone who is involved in the overall process--human factors groups, analysis groups, evaluation groups, design groups, etc.--into a single unit. Call this unit "crew systems," and then, of necessity, management will have to come to you. You then have the possibility of making yourself heard. I realize that implementation of this approach is not an easy task, but I would say we have done so very successfully at The Boeing Company.

The third major problem is our need for better data on the costs of designing a crew station. Invariably, when we try to sell a system to management, we need precise data on what something costs and what savings may be possible. I would recommend that we form a small group to continue working on this problem.

I would also like to mention a few other problems in crew station geometry and workplace layout that warrant attention. First, we need some changes in the methodology we use to evaluate our designs. I think we would all agree it is essential that we continue to develop and improve computer-aided design methods. Such a tool would not only permit industry to make rapid design changes, but would also enable government agencies to evaluate crew systems geometry and design within a reasonable amount of time. Furthermore, if we were able to provide the customer with a computer tape that defines the proposed crew station design, we would eliminate the potentially dangerous current practice of trying to explain the entire system in a 20-page section of the proposal. As things stand now, if something if left out of the proposal, or not explained sufficiently, we rarely get a chance to correct the deficiencies.

I would also recommend that we collect and publish up-to-date anthropometric data and that we place greater emphasis on body positioning. Body position can be very important in crew systems design since it necessarily varies with specific tasks and mission segments. Finally, I think we need improvement in our mockup evaluations. Our subjects should be better prepared about what and how they are expected to evaluate, more carefully selected, and given more time in the mockup.

CONTROLS AND DISPLAYS IN CREW SYSTEM DESIGN

SECTION VI

CONTROLS AND DISPLAYS IN CREW SYSTEM DESIGN

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Abstract: *This paper presents an assessment of the state of the art of displays and controls in crew station design. The hardware aspects are examined first, and it is concluded that advances in display technology are not paying off in enhanced operational capability because problems of operational usage have not been dealt with. The deficiencies in the design process are then enumerated and related to the operational usage issue. Recommendations are offered for achieving a development program that balances the development of hardware technology with research on problems of operational usage of displays and controls in the mission context.*

INTRODUCTION

The control-display area seems to be fraught with contradictions: status for funding and development is low, yet criticism for failure to progress is great. Concern in planning and development of systems is negligible, yet the percentage of blame for deficiencies in the finished system is high.

Often a company representative will stop by and indicate that his company has a little slack and would like to pick up the display business. He has 15 minutes to spare and would like a rundown on the state of the art and the most challenging problems. Unfortunately, the higher echelons (military and industry) recall the simple gauges of World War I and World War II and tend to relate to the salesman who has 15 minutes to spare in catching up on the displays of the world.

With regard to the remarks of Mr. Romero, in many respects we are where we were at the end of World War II. Straightforward engineering has been progressing, it is true; *but* we, collectively, have not been effective in achieving the payoff--adequate improvement in operational capability. This is the heart of the issue in controls and displays.

First I'd like to make some comments about the hardware aspects and then continue on into some detail about the relationship of controls and displays to the achievement of the full performance potential in aircraft.

HARDWARE

Displays conventionally conjure the picture of instruments arranged on a panel. With regard to the gauges themselves, we are seemingly in relatively good shape. Many of them represent, however, the technology developed in the decade following World War II. This class has reached a relatively stable level of performance and reliability. But there are many problems even on the hardware side which remain to be solved.

RELIABILITY

Those electromechanical instruments which have progressed beyond the round dial type to greater sophistication do not yet have the reliability needed for production purposes. We are experiencing MTBF's as low as 25 hours on some components. This means that the instruments must be replaced many times during the life of the aircraft as the life expectancy of the instruments is based upon total running time. This includes both ground time and flight time. When you consider that ground operating time is included, and often represents as much as 50% or more of total usage, this is a truly deplorable situation with respect to useful inflight usage.

SIZE/WEIGHT

The more sophisticated, newer type of electromechanical instruments tend to be bulky, heavy, and expensive. The advances in microcircuitry have been applied, but there has been little comparable activity in reducing overall size and weight. Full advantage of breakthroughs in materials, such as plastics, has not been attempted, much less realized.

NEW DISPLAY TECHNIQUES

Other means are now being explored for presenting information to the pilot such as electronic and optical devices.

Cathode Ray Tubes are being employed on a wider basis, but have not achieved an adequate degree of reliability. Advanced display devices, which include such things as electroluminescent, gas discharge, and light emitting diodes, are being introduced slowly. Holographic techniques are being investigated for application to the display area. None of these has, as yet, been employed on a widespread application basis. They are all in the early stages of demonstrating applicability to display problems. Optical type devices are enjoying greater usage primarily in the area of head-up and map-projection displays. Relatively compact devices are now in existence which make installation more feasible. However, weight and field-of-view continue to be significant drawbacks.

In summation, the techniques or media for generating primary displays have advanced through applied research and exploratory development and a prime hurdle now is that concerned with the final engineering for applications and for production experience.

ANCILLARY DISPLAYS

In terms of mechanical display devices, switches and knobs are a significant factor in conveying information to the pilot. He must scan the position of the switches, etc., to determine the instrument's mode of operation. Thus, the positions of the handles, switches, and knobs are important ancillary types of display devices. These mechanisms have been essentially unchanged for the last 20 years. There have been some advances in attractiveness of switches. However, these relatively minor improvements have come as a consequence of innovations brought about by the computer industry, which is a high volume consumer. This area desperately needs attention to bring the functional capabilities of avionics control devices up to the level required for exploiting the power of the airborne equipments being provided to the pilot.

In addition, the pilot is provided with warnings, caution, and advisory information by means of lights, message panels, and mechanically actuated indicators that are located in various parts of the cockpit.

From a system technology viewpoint, progress has been made toward providing functionally integrated and correlated display data on the electronic and optically generated displays. However, many of the instruments and the warning, caution, and advisory devices located throughout the cockpit are treated as individual elements rather than being integrated within the pilot's overall display system.

ASSESSMENT

Even though I have mentioned a number of problems, we can say that among the engineering groups the limitations and needs of hardware technology are understood and are receiving considerable attention. *The real and limiting problems stem from problems of philosophy, organization, direction, and criteria.*

To be blunt, the display area is in a deplorable mess. The state of the art in the design and supporting technology of displays has fallen critically behind in its capability to exploit the potential afforded by combining the world's best aircraft and pilots. Display technology is not paying off in terms of enhancing operational capability. However, there is more at stake than the credibility of display design. The fundamental issue is the realization of the full potential of piloted aircraft in meeting the responsibilities of military and commercial aviation.

This assessment may come as a shock to those familiar with the resources being expended upon display technology, and in a more general sense, crew station technology. The assessment will certainly be disputed by those who measure progress in terms of the numbers of new gadgets introduced into advanced aircraft. But these indices of progress are not valid. Certainly, the expenditure of money and the creation of new devices creates an illusion of progress. But, in reality the superficiality of the approach has tremendously worsened the problem for pilots, who are left to cope the best they can in accomplishing mission objectives with cockpit equipments that do not take into account their needs in a fluid and often hostile environment.

A serious deficiency, then, is our capability to harness the remarkable advances in the underlying technologies of information display in order to serve the needs of the pilot. Unless the pilot is given the information he needs, when he needs it, and in a form that exercises his decision-making attributes properly, we can hardly expect to advance the operational capability of piloted aircraft.

The issue now hinges upon our ability to determine not only how to mechanize but *what* to mechanize that meets the needs of the pilot in the environment in which it will be employed. This requires that the research being conducted now along basically technology lines be *augmented by research into piloting operational usage*. The latter type requires that a change be made in kind from research being done now for engineering purposes. More of the same will not suffice.

Although not generally recognized, the state of the art in displays is at a pivotal point in its development. A quantum jump in technology--and all that this implies in terms of skills, resources, organization--is required to advance the state of the art into a configuration that is truly capable of dealing with a systems problem that includes the impact of the operational usage in the design process.

For years, display designers have been occupied with the engineering or hardware aspects, and appropriately so. As we have seen, significant progress has been made in this fundamental area. An inability to mechanize severely constrains our options in providing the pilot what he needs. Now, we must expand our concern to the pilot within the context of the operational environment. Unless we adjust, the discipline of display engineering is faced with employing subsystem methods and techniques to solve a systems problem. The success or failure in fulfilling our responsibilities as display designers hinges on how well we negotiate the transition from a basically hardware orientation to an operational usage orientation.

An example is in order to show the sad plight of affairs in the area of operational usage. There are a number of intuitively appealing head-up display systems on the market. Yet, there is insufficient understanding of the role of head-up displays in low visibility landing. What is the problem? Where does it fit? How is the pilot supposed to use it, particularly when the autopilot is turned on? How does the availability of a head-up display affect the first-officer's role? Who is working on this? Who cares? In a meeting on the subject held recently by the Airline Pilots Association, leading display experts of the country--both engineering and pilot types--could not agree on what should be done in the way of development because they could not come to an understanding on the role of the display in the operational environment. The homework had not been done. Consequently, no one could speak with authority. Meanwhile, progress in improving operational capability for see-to-land is, for all practical purposes, frozen in place at 200 feet and one-half mile visibility. And a potential contribution of display engineering remains an item of controversy.

To cite another example: pilot fatigue, disorientation, and misperception in rotary-wing aircraft are three times that of the fixed-wing rate. Spatial disorientation accidents (signifying misuse or non-use of present rotary-wing instruments) alone cost $15,000,000, 75 killed, 150 injured in FY69. The accident rate for rotary-wing landings due to disorientation was found to be two times (on an hours basis, six times) that of fixed-wing aircraft. Rotary-wing *instruments* (not crew) are to blame for the greater accident rate.

Though accidents are very costly, they still occur in only a small fraction of all flights. However, there is an obviously larger, though unknown, decrement in low-altitude, air-mobility, mission performance when accidents do not result. The rotary-wing crew must be able to use the existing information better and to use effectively the new information being developed.

The examples serve to illustrate the price that is being paid for ignoring the true nature of the systems problem in the design process. We are not arguing on theoretical grounds for casual or academic or empire building purposes; just the opposite. The real-world aspects demand that we take the display design problem as it is, not as we would like it to be; and that we recognize the difficulty and the dedication that it will take to break the strangle hold that presently blocks orderly progress in making display technology pay off in terms of operational capability.

DEFICIENCIES IN THE DESIGN PROCESS

The deficiency in the area of operational usage is quite simple to describe. However, we have had no effective means at the moment for defining and incorporating the implications of operational usage into the design process. In effect, the science of display engineering, in flight control terms, is open loop. The science is on the verge of going unstable because of the fantastic pressures created by rapid advances in the aeronautical and avionic sciences on one hand and the requirement for enhancing operational capability at lower cost, on the other. The deficiency is the total lack of capability. The deficiency is the road block to progress. There are elements of the deficiency discussed below which must be addressed.

LACK OF GENERAL RECOGNITION

The importance of operational usage information to the design process is recognized universally. In fact, one cannot find a person who does not desire, indeed demand, that the pilot's needs be attended to in the design. Rather elaborate procedures are

established for allowing the "pilots" to make their inputs. Many responsible cockpit designers would feel personally affronted if it were suggested that they did not have all bases covered in regard to pilot desires. So what is wrong? *There is a complete lack of understanding as to what is involved in coming to grips with the operational usage issues at the working level.* This is an area in which every pilot considers himself to be somewhat of an expert. The engineer prides himself on being able to listen to a pilot and translate his inputs into engineering criteria. As with an iceberg, we delude ourselves on the size and the complexity of the problem by what we see, personally. The lack of understanding and appreciation is exacting a deadly price, literally, in terms of both lives and money. In effect, an overwhelming number of people in display design just don't know what they are doing. They work with very fundamental issues in which a pilot's life is involved. Many are not even aware of the consequences. Thus, they have a tendency to be casual and rather academic in their approach to the cockpit design.

PEOPLE

There are very few people who have the necessary skills to deal with the crew station/operational environment interface problem. One of the reasons is the lack of understanding of the importance of the area discussed above. Certainly, the relatively recent description of the problem area is partly the reason for the modest number of people qualified to work on operational usage issues. And, the lack of funds has reduced drastically our opportunities to train people. The technical universities are not providing qualified graduates to us in this area and for good reason. We in the operational organizations alone have the operational experience; therefore, we must be prepared to train and develop our people from within.

Additionally, management in general is inadequately informed as to criteria for selecting these people. Many, many times they are selected on some criterion other than demonstrated or known capability to deal with the type of problems with which they must cope.

PROCEDURES/METHODOLOGY

The lack of scientific method in measuring and comparing problem-solving capabilities not only of the cockpit as a whole, but even of individual displays, precludes a rigorous attack on the operational issues. Experimental procedures can be used to determine the ability to read and interpret displays. However, we do not have any system of numbers for evaluating the relative merit of a display, a group of displays, or a total cockpit system design in terms of its applicability to a mission problem. We still do not have an adequate method of measuring and describing pilot workload. Consequently, there is a real problem in expanding the role of the pilot to that of a "pilot-manager" with any degree of scientific control.

At the moment, we are limited largely to pilot opinion in the evaluation of crew station suitability. This is not all bad. But the procedures and methodologies for developing and measuring the effectiveness of cockpit configurations must be dramatically strengthened if the display science is to keep pace with its associated engineering disciplines.

We are encouraged by the great amount of work being performed at the theoretical level. Over the past ten years we have witnessed tremendous progress in the growth of theories, from information theory to physiological models--relating the measurement of cockpit "goodness." The problems lie not in the lack of theories but rather in the adequate application and testing of the models in an operational context. All too often the models are developed in a somewhat "ivory tower" atmosphere and then tested in a simplistic manner. It is our responsibility as control/display designers to apply the models in an operational context and point out their weaknesses so that, through a constant interaction between the designer and the theoretician, more useful "real world" models can be developed.

ORGANIZATION

There are two aspects of organization that need to be recognized as deficiencies. First, a sound working relationship between the display design organization and the user must be established. Users often have a strong suspicion of any development agency and not without justification. But any barrier that may exist must be eliminated. The pilots are our customers. At the moment, we do not have the needed rapport, the methods, or the organization to integrate the user into the problem definition, solution development, and hardware evaluation in any effective way.

An aspect of organization with which the military display designer must contend has to do with his relation to the hardware and weapon system development groups. We have found in our dealings with these people that they generally lack an appreciation for what we are trying to tell them about the operational usage aspects. Although they would deny it vehemently, hardware development is concerned primarily with engineering aspects. How can we work our technology into the process in an orderly and effective way with some authority? Yes, the format process is well known. But here, we are talking about people-to-people types of interactions. An example is in order.

In 1955, the whole panel concept for the F-105 was moved from initial design through prototype fabrication, test, and installation into the fleet. Returning pilots from SEA report that the F-105 has the best panel of any aircraft the Air Force has. Why? Well, the design did represent significant improvements technically speaking. But there is more involved than that. The organization was such, at that time, that the hardware people were constrained to pick up the prototype and build it per our specifications, which were derived through consideration of pilot and mission needs as well as hardware considerations. Unhappily, this type of hand-off to the hardware vendors is not easily achieved, probably because of inadequate understanding of the issues involved. More generally, development and procurements are based largely on engineering criteria, not piloting criteria. If we are to integrate the operational usage implications into the design process, we must simply get the horse before the cart. The pilots' needs dictate what should be put into the cockpit, not what the hardware engineer can provide in the way of new gadgets.

PROJECT MANAGEMENT

An issue of fundamental concern in resolving this deficiency is to be able to control people and resources in a rapidly expanding area of technical concern. We must discharge our responsibility at the lowest possible cost. We must get the best from our people. And if that is not good enough, then ways must be found to improve their capability. Effective project control is the way to accomplish these objectives. Experience has shown us that problem-oriented research in exploratory types of endeavors, where multiple projects that contribute to a common goal are being conducted simultaneously, is a tricky business. It requires special attention to develop an understanding of its unique set of requirements and, more importantly, how to interface the existing project control system to the requirements imposed by the nature of the operational usage problem. The requirements have been defined in their modular form through an extensive, real-time, structured investigative process. What is lacking is an integrated control system capable of conducting trade-off studies interrelating schedules, resource requirements, and budgeting for a multi-project type of activity in a high-risk environment. Developments must be pushed in this area if effective control of the research is to be realized and technical responsibilities discharged in a timely and cost-effective manner.

WHAT CAN BE DONE

In evaluating the assessment of the display area, one must accept the premise that a balanced program in hardware and operational usage must be achieved if order is to be brought out of chaos. At the moment, the overwhelming emphasis is on hardware. The unbalance is the root cause of display technology not paying off in operational capability. In both absolute and relative terms, the cost required to develop an operational usage research capability is substantially less than that being spent on hardware developments. But, the costs are at least an order of magnitude greater than what is being budgeted. Understanding of hardware requirements should only come as a consequence of knowing the pilots' control-display needs. It is vitally essential that the sequence of research developments be placed in proper sequence. For these reasons, we choose to discuss only operational usage in this discussion. By limiting our discussion, we hope to show the deep concern we have for obtaining the needed recognition for operational usage research and concurrently protest the over-emphasis that hardware has received.

In a general way, the key or pivotal issue which deserves treatment is the organizing and describing of this infant science. The following aspects must be emphasized.

EDUCATION

A hardhitting education program must be devised and directed to people at all levels. Certainly we must undertake to effectively communicate the nature of the problem and the importance of considering programs for attacking it. We must undertake to gain the sympathy of the hardware people, if not the understanding. Within our research program, we must educate and inform managers on what they must ask for, what they must use in selecting people, and then the criteria for judging their work. The project personnel must be provided a more formalized type of training program in getting their skills and capabilities up to speed and assuring that the individuals remain in the forefront of the state of the art.

METHODOLOGY/TECHNIQUES

A very determined and concentrated effort is required in expanding and developing the methodology, the techniques, the problem-solving methods to be used in performing the design for a total crew station responsive to meeting the pilots' needs in the operational environment. In this process of development, techniques for evaluating the resultant designs must be included. There must be some scheme of numbers developed for the effective measurement of the relative merit of the proposed designs. This must be carried on through the operational employment aspect of the problem. Means must be devised for describing, defining, evaluating, and validating designs in the operational context.

ORGANIZATION

Organizational revision is absolutely necessary for purposes of controlling and directing work in this area in some orderly, well conceived manner rather than the spasmodic fashion which is wasting literally millions of dollars. Organizational consolidations need to be made so as to permit more effective use of the few skilled people presently available.

PLANNING/BUDGETING

Far too much money is being expended for the return being obtained. The real problem here is that it is uncoordinated expenditures. It seems to be spasmodic and related to buzz words rather than to logical planning. Much of the expenditure is for attempting to compensate, after the facts, for inadequate provision in the original development process. To say it again: this stems from inadequate understanding, at management levels, of the issues and trade-offs which are operating.

TOTAL SYSTEM ORIENTED EFFORTS

Specific vehicle/mission oriented programs should be undertaken to develop display systems which provide for exploitation of the full operational potential of the vehicles. As an example, a developmental program could be undertaken to define and develop the crew station area of VTOL aircraft over its entire speed range. The control information must be provided to the pilot in a way that is consistent with flying the aircraft naturally. The pilot must be kept fully informed as to the aircraft status if he is to function effectively as a flight manager. The confidence that the pilot has in his flight-control system rests fundamentally upon the quality of the situation information. The program must also take into account the possibility of design variations for subsets of problems such as carrier and shipboard operation as contrasted to unprepared landing site operation.

ONE APPROACH TO THE PROBLEM

A foundation for attacking the operational usage problem in a rigorous, straightforward fashion has been established within the Air Force Systems Command under Project 6190. It represents one approach to the problem and includes, hopefully, provision for all relevant factors necessary to dealing adequately with the total control-display area.

1. In order to address the problem of information display, we must expand our area of concern to the total crew station in an operational setting. This has required that a very strong crew *system* technology program be formulated and set into motion which considers all relevant factors in the research process. The thrust of the research must be directed to a concern for the problem confronting the pilot rather than preoccupation with a particular piece of hardware. To attain this end, a lead group, the Crew Systems Integration Group, has been established.

2. A large-scale information system has been established to handle the multitude of data relating pilot experience under combat conditions to crew station design. When looking across the many surveys conducted by an unbelievably large number of organizations, we see that data are being produced in fantastic quantity. But, the data are not in a form that can be used. The first step undertaken was to organize the data into a form that can be manipulated for a variety of research purposes. This step has been initiated but has a long way to go.

3. An information system has been set up for the acquisition and maintenance of pertinent reference material on the topic of flight control-display. In contrast to pilot experience data (item 2 above), this reference center deals with information that could be considered as mature data in that technical reports, textbooks, etc., are incorporated into the data base. The Control-Display Information Center is one of the most complete reference centers on flight control-display.

4. An outlet to pilots skilled in the procedures and techniques of instrument flying has been established. It is one thing to engineer a display; it is quite another to use the display in its applied form. A working agreement between the development agency and a flying training/instrument R&D group (IFC) was established for drawing highly skilled operational pilots into advanced display development. The initial effort, having to do with establishing the pilots' control-display requirements on final approach, was a remarkable success. Since that time, the role has been expanded to include problem formulation tasks on instrument problems.

5. Interdisciplinary teams of specialists have been formed to deal with the operational usage problem. A team is composed primarily of avionics engineers, human factors engineers, simulation engineers, engineering test pilots, instrumentation and evaluation pilots, and flight control engineers. Their prime orientation is concern with pilot and mission needs rather than technical innovation for its own sake.

6. Ground-based simulation facilities have been developed and maintained over a period of years. The tools available for researching problem-oriented issues range from full mission simulation, tailored to the needs of flight control-display, through a dynamic mockup which incorporates many of the environmental aspects to part-task simulation. In addition, a number of capabilities have been developed for examining crew systems in the earliest phase of development, e.g., stop-motion photography.

7. The requirements for a project control system have been defined for dealing with the management requirements. Management of this highly specialized type of research is considered to be a part of the technical job, for we must realize the maximum return on each dollar spent. This demands that we be able to conduct trade-off studies on alternative approaches prior to project go-ahead, monitor the progress of the work so there will be no "surprises," and evaluate the technical performance upon completion.

8. A strong technology in the elements of the cockpit system has been established which funnels into the crew system technology program. Major elements are display elements, primary controllers, and man. Supporting elements are advanced display techniques and advanced display principles, among others.

From this description, one begins to get an appreciation of what we are talking about when we say that the operational usage problem is an order of magnitude more complex than building displays. Initial effort has been concerned, to this point, more in defining and establishing the functional capabilities needed for attacking the problem. This has been a necessary first step. The extent to which we must become involved in dealing with operational usage is at the very least impressive, if not overwhelming.

It will be noted that a good deal of the effort is directed to people, their education, and control. This is a requisite in ordering a new technical area. The people qualified to deal in the area of operational usage are few in number, and those that are qualified lack the facilities and resources for adequately handling the job.

SUMMARY

Operational usage means how well, or how effectively, the hardware technology is being applied to solving the problem of conveying information to the pilot when he is executing his mission. To be frank, the state of the art of this aspect is in its infancy. It has only been within the last three years that we have begun to recognize the nature and magnitude of the problem and have some appreciation for what must be accomplished for effectively dealing with it.

In absolute terms, the state of the art is pitifully inadequate. This is not surprising when one considers that the concern for operational usage is a concept which has received relatively little attention or emphasis in comparison to hardware. The understanding of what is involved did not spring full grown into existence. As in all matters of scientific endeavors which require revolutionary rather than evolutionary changes in thinking, the form of the problem surfaced over a considerable period of time. Thus, our understanding of what needs to be done at this stage, far out-distances our performance in attacking this problem to date.

Upon looking into the application aspects we find that dealing with the operational usage problem is at least an order of magnitude more complex than developing the tools of the display science per se. The totality of the problem must be understood as a whole: the conditions, the pilot, the equipment, the environment, the mission, and the vehicle.

With severely limited resources, little more than intuitive judgment could be used for looking into the operational usage aspect during the last three years. The approach taken was to probe this highly complex area in a rigorous fashion. There are those who would argue that we do have a viable capability in terms of incorporating operational usage into the design program. To these critics we would reply, "Responsible people have been talking about this aspect for some time in rather glib terms." However, the rising chorus of pilot disillusionment with what is being provided in the fleet gives us cause for discounting these critics. These people have a tendency to talk system design in concept, but practice subsystems design in application.

The state of the art of advancing the pilot's capability to exploit the power of today's aircraft is dreadfully inadequate. When the effort expended on this aspect is contrasted to the expenditure on hardware, it becomes obvious why the disparity exists. Unless a balanced program in hardware and operational usage is achieved, the situation can only get worse, not better.

DISCUSSION ABSTRACT

• *Dr. Bernberg, Litton Systems, Inc.:* I do agree with you to a great degree about the limitations of studies made during the past 15 or 20 years. However, some successful work has been accomplished in this period. For instance, I remember two studies of blind landing and low visibility and their mechanization in 1964. One study made at NASA Ames on blind landing using a CRT type display was, I believe, quite successful. In another study, Bill Gracy (NASA Langley) investigated blind landings in a rotary wing aircraft equipped with variable stability augmentation and a CRT type display. NASA Langley also did extensive work on information requirements for display symbology. That was eight years ago. Do the services not talk to each other?

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* Certainly I agree that systems work has been done on all-weather, low-visibility, and zero-visibility landings as far back as World War II and repeatedly since. However, my concern is making sure we have a system that can be used routinely and with confidence by average - not just exceptional - pilots. And right now it is a fact that certain pilots who have confidence in this equipment on the experimental level evaluate the equipment capability somewhat differently when asked if they would actually fly on an airline which used similar equipment.

• *Dr. Pierson, University of Southern California:* Partially in answer to this last question and partially in support of what you've been saying, we have conducted surveys with Army aviation safety officers and Air Force flying safety officers, asking for ad lib statements about man-machine or man-environment incidents they have encountered. A significant proportion of the incidents were the result of design-induced disorientation. So, yes, we have known that not enough is being done for a long time and no, we are not doing anything about it.

• *LCOL Chubboy, Federal Aviation Administration:* The FAA has had considerable difficulty in assessing cockpit workload in commercial aircraft. My question to you is, how would you propose to acquire the necessary performance data in the operational environment without letting the data acquisition system, whatever it may be, interfere with the performance of the mission. That one has bugged us a little bit.

• *Mr. Kearns, USAF Flight Dynamic Laboratory:* That is not an easy problem. We have had some experience, not in the total mission context but in at least some flight phases, and it seems to require a fairly expensive operation - many, many flights. In fact, we have spent a great deal of time specifically on the landing problem - and we have made more than 10,000 landings in six years which were rather completely instrumented. Perhaps we are just accumulating a mass of data over a period of time, but these data have greater validity than any results we would obtain by having the equipment itself interact and bias the results of the data in the way that you are referring to. The process is slow and painful - defining small increments of the problem at a time, attempting to correct them, re-flying the system, and making all of the measurements again.

• *LCOL Chubboy, Federal Aviation Administration:* Do you agree with Fred Hoerner from the Naval Air Test Center who advocated the use of dedicated aircraft?

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* I am sorry there was nobody from Cornell present to respond to this comment. We have a dedicated aircraft referred to as TIS, total inflight simulator. It is a variable stability T-130 aircraft with an extra nose added onto it. A heavy complement of computers is onboard so that we can vary all the dynamics of the aircraft in all three axes; the cockpit itself can be modified to virtually any kind of configuration. The large size of the aircraft is the only limitation. In the future we hope to have a comparable aircraft in a higher performance region. But we agree wholeheartedly that dedicated aircraft are valuable in solving crew station design problems.

• *LCOL Chubboy, Federal Aviation Administration:* For operational performance as well, as opposed to pure systems evaluation?

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* Yes sir, we must have the necessary tools, have them long enough, have them available when we need them, and have them dedicated to these kinds of problems.

• *Mr. Naurath, Naval Missile Center:* Mission recorders have proved valuable for testing and evaluating fighter aircraft. They are useful in evaluating human and system performance in an operational environment, and equally useful in evaluating pilot proficiency in a training environment. Yet there is constant pressure to remove or exclude mission recorders from aircraft because of their excessive weight, space, and power requirements. These criticisms may be legitimate, but the technology is available to build mission recorders that are far better than those in use today. Therefore, rather than lose a proven T&E tool, I feel we should be spending more time and resources in developing mission

recorders that are lighter, smaller, require less power, and provide more data than those being used today.

• *CDR Hammack, Office of Naval Research:* Can you comment on the correlation between the pilot's preferences and his performance in terms of control and instrumentation?

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* This area still has some aspects of the unknown. Controlled experiments have shown that performance measurement data and pilot preference data often do not agree. We tend to suspect that the experimental situation has limited the validity of the measured data. There is also an aspect of the pilot in this that seems important, but we do not seem to be able to pin it down very well. Some people refer to it as the "happiness" or "satisfaction" factor. If the pilot is going to do the job over a long period of time, it would seem that his attitude or personal evaluation about the utility of a system should also be significant. To what degree, we do not know. Because we have so often run into this disparity between subjective reaction and objective measurement, we are inclined to think that there is something that needs to be measured that we do not know about.

• *CDR Wherry, Naval Air Development Center:* From the display standpoint, do you feel that moving-base simulators with visual real-world simulation would perhaps be more cost effective than dedicated aircraft since one does not have to go through the complete mission to arrive at the particular mission segment you want to examine?

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* I wish I had the answer to that. We feel that we are arriving at the point where it is more expensive to operate simulators than to operate dedicated aircraft. However, there are still some persuasive arguments in favor of simulators. For instance, you can control the simulator situation more thoroughly, you can freeze some of the parameters, and you can stop the simulator in mid air. And, of course, simulators are safe.

• *Dr. Besco, American Airlines:* I am concerned that our test pilots are not adequately trained to evaluate the type of variables in the type of situations that we have been discussing this afternoon. If you examine the advances we made in other areas, you will find that the test pilot has made significant contributions. But we had to train the test pilots adequately before they could make this contribution. When we became concerned with performance, we started teaching test pilots about aircraft performance. And when we got involved in stability and control, we included fairly exhaustive stability and control training as part of most pilots' curriculum. Now, I wonder how we might get the test-pilot school curriculum modified to include training on how to evaluate controls, displays, and the man-machine interface. Also, how can we incorporate such training into the civilian certification process?

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* Over the past ten years we have been trying to cope with this complex problem with limited success. We presently have two different groups of test pilots in the Air Force. At Wright Field we have conventional test pilots who are concerned with the equipment - how it works, what the bugs are, etc. But at the Randolph Instrument Flight Center, the test pilots are asked for their subjective reactions. Some pilots are quite skillful at translating their needs into concrete terms; for instance, indicating what they need on a display, or why certain flight techniques need modification. We would like to have a course to train pilots in this type of translation, but so far we have been limited to informal training accomplished during a long-term relationship with the pilots.

• *Mr. Naurath, Naval Missile Center:* We do have DoD human factors specifications concerned with controls and displays design. Yet the application of these specifications, even though mandatory, is very difficult. Typical reasons for not meeting a specification include: lack of funds, use of the specifications as guidelines only, the need to use GFE or residual equipment not subject to these specifications, or the fact that a particular provision (letter size and distance) is not valid. I think we must find a way to ensure that human engineering design standards can be developed and effectively used by both program managers and human factors personnel at all levels of the design process.

• *CAPT Burke, Air Line Pilots Association:* You are quite modest about the contribution of the Instructor Pilot Instrument School program. These are the only people in the world who have flown your head-down displays in the low-visibility environment. I would like to ask why you have not yet evaluated the head-up display in the same environment?

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* You mentioned we were too modest about the instrument pilot group. We certainly do not mean to be. They have done more and have more capability, we think, than any other group in the world. With regard to the HUD, we are aware of the problem and work is being done. Unfortunately, resouces limit our rate of progress. Where it used to take one engineer to develop an instrument and two or three to test it, now we may need as many as 45 people. Where an expensive instrument used to cost \$50,000 to \$100,000, current costs

easily exceed $3,000,000. Because of these costs, there is a limit to how many things we can take on at any one time.

• *Mr. Mueller, Army Aviation Systems Command:* I concur with your statement that the cause of many helicopter accidents can be traced to the use of displays and controls that were not originally designed for rotary-wing aircraft. This problem has been haunting Army aviators. Displays and instruments have been added to helicopters in a piecemeal fashion, and they have not kept pace with mission requirements. I would like to recommend that this conference consider the establishment of a sub-group to address display and control problems in rotary-wing aircraft.

WORKSHOP PROCEEDINGS

CHAIRMAN: MR. JOHN H. KEARNS, III USAF FLIGHT DYNAMICS LABORATORY

WORKSHOP DISCUSSANTS

MR. JOHN C. ALEXANDER, Computing Devices of Canada
MR. BERNARD F. AMOS, Grumman Aerospace Corp.
MR. PAUL A. ANDERSON, Honeywell, Inc.
CAPT WILLIAM P. APPLEGATE, USAF Instrument Flight Center
MR. GERALD C. ARMSTRONG, Bunker-Ramo Corp.
MR. RAYMOND C. BASSETT, ITT Avionics Division
MR. DEAN B. BAUMUNK, McDonnell-Douglas Corp.
DR. RAINER K. BERNOTAT, Forschungsinstitut fur Anthropotechnik
MR. SIDNEY BLATT, Federal Aviation Administration
LTCOL J. D. BOREN, USAF Aeronautical Systems Division
MR. JAMES M. BRAID, Ferranti Ltd
MR. KEN L. BURROUGHS, Air Line Pilots Assoc.
CAPT RICHARD L. CAMPBELL, Army Aviation Human Research Unit
MR. WALTER L. CAREL, Hughes Aircraft Company
MR. DONALD P. CHECKWICK, Army Aviation Systems Command
MR. WILLIAM A. DALHAMER, Honeywell, Inc.
MR. RICHARD N. deCALLIES, United Aircraft Company
CAPT J. LARRY DeCELLES, Air Line Pilots Assoc.
MR. JOHN C. DENDY, Hughes Tool Company
MS. PATRICIA A. DU PUIS, Northrop Corp.
MR. EUGENE F. EBRIGHT, Northrop Corp.
MR. DELMAR M. FADDEN, The Boeing Company
DR. CHARLES A. FENWICK, Collins Radio Company
MR. DIETHER FINSTERBUSCH, Northrop Corp.
MR. JOHN J. FRANCEK, Federal Aviation Administration
MR. CARL S. FRASER, Hughes Aircraft Company
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MR. PAUL E. GREER, Vought Aeronautics Company
MR. BERNARD S. GURMAN, Army Electronics Command
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MR. SAMUEL E. MERRIFIELD, Army Aviation Systems Command
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MR. JACOBUS J. P. MOELKER, National Aerospace Laboratory
MR. LESLIE D. MOORE-SEARSON, Marconi Elliott Avionics Ltd
MR. N. THOMAS MUELLER, Army Aviation Systems Command
MR. MILES R. MURPHY, NASA Ames Research Center
MR. DAVID A. NAURATH, Naval Missile Center
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DR. STANLEY N. ROSCOE, University of Illinois
MR. WALTER C. RUGH, Northrop Corp.
MR. JOEL T. SALZ, NAS, Los Alamitos, Calif.

Continued on next page

MR. PETER P. SCHMIZ, Northrop Corp.
MR. SCOTT B. SEWARD, Hughes Aircraft Company
MR. ROY S. SMITH, Texas Instruments, Inc.
MR. PAUL J. STEPHENS, North American Rockwell
DR. WILLIAM F. STORM, USAF School of Aerospace Medicine
MR. THOMAS C. SUVADA, Astronautics Corp. of America
MR. CHARLES B. THOMAS, Naval Air Test Center
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MR. V. G. VADEN, The Boeing Company
MR. DAN W. WAGNER, Naval Weapons Center
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MR. WAYNE R. WILKIE, McDonnell-Douglas Corp.
MR. JACK WOLIN, Naval Air Systems Command
MR. FRANK A WULF, General Dynamics/Convair
MR. NATHANIEL K. ZEDAZO, Astronautics Corp. of America

ABSTRACTS OF WORKSHOP PAPERS

AN OPTIMIZATION TECHNIQUE FOR THE NUMBER/TYPE OF COCKPIT CONTROLS

Bernard F. Amos
Grumman Aerospace Corporation

The selection of the optimum number/type of cockpit controls is a major design problem. This paper describes a linear programming technique that provides a means of comparing many control configurations and yields guidelines for selecting the best one.

Linear programming deals with the problem of allocating limited resources among competing activities in an optimal manner. The procedure requires the development of a mathematical model that represents all aspects of the problem.

Two models will be described using graphical solutions to aid in visualization of the concept. In addition, a generalized mathematical model is developed specifically for application to cockpit controls.

A REAL WORLD SITUATION DISPLAY FOR ALL WEATHER LANDING

J. Larry DeCelles
Edward J. Burke
Ken L. Burroughs
Air Line Pilots Association

This paper describes a flight data display for use in aircraft approach and landing under all conditions of visibility from CAVU to zero-zero. It is particularly notable that the display does not require a flight director. The display was developed by application of the building block concept and can be operationally implemented in the same manner. In its simplest form it provides airborne self-contained glidepath guidance for use in visual flight conditions and in its most sophisticated form it provides total information for manual landing, or for monitoring automatic landing, and roll-out during zero visibility conditions. The basic concept is derived from the authors' observation that pilots have no difficulty landing aircraft by reference to the original head-up display, i.e., the real world as seen through the windshield in clear weather. The display advocated is extremely simple and uncluttered. Essentially a situation display, it employs a minimum of computer input. Being usable in all conditions of visibility, the display would lead to the development of pilot confidence and competence and drastically reduce training time. The authors contend that head-up display of symbology similar to that described is urgently required for see-to-land approaches and will be essential for pilot acceptance of automatic landings in actual non-visual conditions.

VSTOL TERMINAL GUIDANCE HEAD-UP DISPLAYS: A REAL WORLD EVALUATION

Frederick G. Hoerner
Naval Air Test Center

The inability of present-day instrument displays to provide an all-weather approach in VSTOL aircraft and the failure of simulator developed displays to provide usable display formats and dynamics without expensive changes after production has led the U. S. Navy, through the NAVAIRSYSCOM, to develop a real world evaluation of head-up displays for VSTOL. The test bed will be a CL-84 twin turbo-prop tilt wing airplane which is capable of flying safely throughout the VSTOL transition range, with accommodations for a subject pilot, a flight safety pilot, and sufficient room/power for the programmable display avionics and data recording systems. Prime emphasis will be on a data related pilot performance evaluation of the head-up display and its dynamics for terminal guidance.

MULTIFUNCTION DISPLAYS--THEIR ROLE IN THE COCKPIT

Thomas C. Suvada
Astronautics Corporation of America

Considerable effort has been and is being undertaken in the development design, and production of multifunction cathode ray tube (CRT) displays. This paper presents a descriptive overview of the multifunction display--what it is and how its use enables flight crew members to improve their performance while decreasing their workload.

TACTILE INFORMATION PRESENTATION (TIP)

David E. Thorburn
USAF Aerospace Medical Research Laboratory

For years researchers have been trying to develop ways to present essential information to a pilot without increasing the information load on the already overworked audio and visual channels. Although many people have considered using tactile warning as a possible solution, embodiments of the tactile device have been too encumbering or the tactile signal too unpleasant for practical use.

This paper describes TIP (Tactile Information Presentation), which is a device that produces a distinct tactile stimulus by inducing a high-pressure pulse of air into the pilot's anti-g suit. A special circuit designed to sense a preset voltage from either the angle-of-attack transmitter or an accelerometer triggers an oscillating circuit which induces a high-pressure pulse of air through a bypass in the standard anti-g valve and into the pilot's g-suit.

Experimental testing on the Aerospace Medical Research Laboratory's centrifuge has shown three cycles per second to be the most distinct pulse frequency. Although g-limit information could also be presented, the most useful information seems to be an angle-of-attack signal which can be used to indicate maximum maneuvering alpha. Since a useful signal is obtained even when the g-suit is not inflated, landing angle of attack may also be presented which is of interest to the Navy with its special information requirements for carrier landings.

This paper gives a physical description of the TIP devices, centrifuge test results, and the results of Air Force flight tests currently being conducted on F-4s and an F-100. Possible future improvements and developments are also discussed.

A METHODOLOGICAL APPROACH TO DISPLAY DESIGN

James D. Wolf	Paul A. Anderson	Bernard S. Gurman
Honeywell, Inc.	Honeywell, Inc.	U. S. Army Electronics Command

This paper summarizes a methodological approach utilized in two studies performed under sponsorship of the Joint Army-Navy Aircraft Instrumentation Research (JANAIR) Program. These studies had the objective of determining vertical-life aircraft display subsystem requirements for manually controlled formation flight and steep-angle approach to landing under Instrument Flight Rule (IFR) flight conditions.

Because of the complexity of the control task involved, a high degree of pilot display augmentation or quickening was required. The approach taken to define display augmentation requirements involved the use of both control-analysis techniques and man-in-the-loop task simulation in four basic stages of study conduct.

Results of these studies have demonstrated this approach to be an efficient means for establishing display-augmentation requirements for complex manual-control task performance, and have further indicated augmentation characteristics to be a more significant determinant of complex task performance than the format of the display within which this information is integrated. Preparations for flight-test validation of simulation study results are in progress.

WORKSHOP HIGHLIGHTS

• *Mr. Mueller, Army Aviation Systems Command:* I came here to find out if you people have the answers to a number of questions about head-up displays. I have gone to human factors people and gotten nothing, in fact, I find that you have not even decided or started to decide yourselves what the application of the head-up display is. So, how can you expect us to come to you when we need help.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* That is one of the points we are trying to get at. In the case of the head-up display, there must be dozens of vendors building equipment now. What is their objective? Is it to sell equipment or to solve a problem? If the industry and the military are collectively concerned with this subject, how can we improve the situation so that in this period of limited funding and resources we can get the most return for our money?

• *Dr. Roscoe, University of Illinois:* I would like to make some comments about the preceding discussion and about the comments made by the representative of program management. I think that we need to determine what is a requirement. This often gets confused with someone's particular piece of equipment. It even gets confused with whether or not it is head-up or head-down. This issue has to do with the organized presentation of information so that the pilot does not have to accommodate inside and outside, up, down, and around the cockpit. It also has to do with determining, ultimately, what information he has to have if he is going to land when it is truly zero-zero, and you cannot see to taxi, even when you have landed. So, the issue is not whether it is head-up or head-down but whether you bring into the cockpit a view that the pilots like to refer to as an independent landing monitor, a means of seeing what is out there even when the view is completely obscured. We may well find that the display should be head-down, all electronic on which you present a forward looking radar or infrared display that penetrates the fog and on which you superimpose the information needed for guidance. So ultimately you will probably have to view the head-up display as an interim device useful for category 2 landings, but not at all in category 3 operations. At that time you have to do better than that, you have to provide a picture of what is out there with the guidance information. And it may turn out, from the standpoint of engineering, that it is more readily put on a high resolution display that is head-down. In that case, you would never have a "break-out" in which you look at the sunlit world with the naked eyeball.

Yesterday or today, I made some comments to the effect that FAA had legally put a price on pilot performance. That price is the only one that is meaningful. The same thing is true in the military for a program manager. One has to view, not the initial cost of a system, but its cost over the life of the system. This includes not only maintenance, but the cost of training crews for safe operation. It also includes the cost of a blunder, or a catastrophe involving loss of life. The true cost goes far beyond the price you can place on that airplane and the people that are in it. In the case of civil aviation, it extends to the entire attitude of the traveling public. So it is essential that you have some means for measuring pilot performance in a meaningful way--a comparison of one set of conditions with another quite different set of conditions, using one common, reliable measure. This long-time problem concerns not only the selection and evaluation of systems, but also the selection of pilots. How do you select and train a man to perform with a very low rate of error, and how do you determine when he has reached that point? Currently the FAA has a certification crisis. In the next few years they will face the problem of re-certifying a million and a half pilots every two years, certifying 400,000 new pilots every year. How do you do this?

Another problem is how do you measure the vital quality we call residual attention, that is, how much attention a pilot has left over after he has taken care of the housekeeping in the cockpit? At the University of Illinois we have been testing a fly-by-wire control system that gives what we call performance maneuvering control. With this system you can call for a given bank angle or climb rate, and as long as you hold the control in that position, the aircraft will continue to perform as commanded with no further adjustment of the controls. This system reduces the blunders made with a normal control system by 90 percent and also greatly increases residual attention. In addition, the residual attention measure is very sensitive. You get significant differences in performance as a function of whether you have one, two, four or eight waypoints storable in the computer. Also you get very sensitive learning effects. The improvement in performance is very steady and very uniform

among pilots, even though there are large performance differences among the pilots. So we are approaching the point where we can put a price on improvement in equipment. We can quantify it in terms of the additional residual attention that it provides in the cockpit. Another price you can put on equipment is its ability to reduce blunders in the cockpit. So some scientific, systematic, rigorous effort is going on that will help a program manager make decisions and put a price on each piece of equipment he puts in the cockpit.

• *LCOL Boren, USAF Aeronautical Systems Division:* A substantial amount of available data suggests that the fly-by-wire system is indeed a good concept. The SPO manager is aware of this, as is the using command. And yet, they are not doing anything about it. Other government agencies and industry have been aware of ideas that have considerable merit and yet have done nothing about them. Someone suggested that we should not have to use an emotional sales approach to incorporate these good ideas into crew station design. But I maintain that, until we have representation at a high enough level to ensure the introduction of new concepts into crew station design, we are going to have to use emotionalism to get these concepts accepted.

• *Dr. Roscoe, University of Illinois:* You say how do we get off of dead center, how do we get any further than we are right now? We know how to do things, why are we not doing them? I have yet to find a program manager who would not respond to numbers or data if they applied to the issue in question. I have yet to find a program manager who did not find comfort in a rational quantitative justification for any decision. I realize that when recommendations are made they are frequently disregarded, but they are not disregarded if they are backed up by appropriate numbers. If you prove you can reduce the total aiming of a missile system from a half mil to a tenth of a mil by virtue of viscous damping and the right control ratios and inertial moments in the aiming system, no program manager in the country would fail to go along with that decision because he has no better basis for making a decision. He is not an unreasonable man, all he needs is something to justify his decision in terms of performance accuracy and dollars.

• *CAPT DeCelles, Air Line Pilots Association:* I would like to respond to Dr. Roscoe's comments about head-up and head-down displays during zero-zero conditions. I used to advocate the type of system he proposed, but it dawned on me that if you do not have a head-up display you will not see the display during the last 75 to 100 feet of the landing approach because you are too busy looking out the window. A head-down display would only be feasible if it were superimposed on a television image. And I seriously question whether pilots will make routine landings with a television image. One other point, I agree with Colonel Boren that the only way you will surmount the obstacles that stand in the way of progress is with emotional arguments. Probably only when we have some serious calamities involving jumbo jets will pilots stop accepting responsibility for things they can't control and stop accepting the pilot error label for landings they were forced to make without adequate guidance.

• *Dr. Roscoe, University of Illinois:* I recognize the problem of not using a system regularly. If a pilot is to make good use of a system for adverse conditions, he must also use it under good conditions regularly so that he is familiar with it. I also recognize that the solution to the landing monitor is less than perfect. However, I think the following combination would greatly improve current systems: an infrared system in the 13 micron region which will penetrate the densest fog; a high-resolution television for use when you have large particles of water; advances in the current, rapidly improving resolution of displays; and location of sensors down by the wheels so that when you are 75 feet in the air your eyes are down where the action is. I believe pilots would use such a display regularly and, in fact, do better with it even on a bright sunny day than they would looking out the windshield from 75 or 100 feet in the air. Further, this combination would eliminate the expensive and complex requirement to bend the nose of the airplane. So I think that a lot of the problems that CAPT Decelles recognizes must be resolved through improvements in the technology used to build the system.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* You said you need your sensors down by the wheels where the action is. How do you know? You say this, but another highly experienced pilot may say that is a bunch of bull, that he does not need this system, that he can fly perfectly well by looking out the cockpit window or that he needs a head-up display even under zero-zero conditions. Another experienced pilot may say I can land with the sacred six and I do not need anything else. How do we know what requirements are valid? How do we prove what is needed? How can the managers make a decision when they find disagreement among some of the leading authorities in the world?

• *Dr. Roscoe, University of Illinois:* Jack, as both you and I know, you have to resort to experimentation. As we have said here today, if you ask for opinions, you get more than you need. We can't base decisions on opinions; we need adequate experimental evidence to prevent this. I have not yet met a man who would make an important

decision in the face of concrete data to the contrary. If we had managers who would look the other way in the presence of concrete data, then we would have a different problem.

• *Mr. Stanton, Jr., NASA Headquarters:* As you probably know, in the Gemini and Apollo programs, we had fly-by-wire and sidestick controllers. When the space shuttle program came along, we spent about three months considering whether we should use minimum or maximum avionics, and finally ended up somewhere in the middle. One of the reasons for this decision was money, cost effectiveness. We were able to quantify the cost of weight, safety, etc., and after putting all these things together, we came up with what you might call medium avionics. This meant that we would go back to fly-by-wire and sidestick controllers. So although the Colonel was worried that progress is not being made, this is evidence that it is being made. We are continuing on in that way. I think that if we are somehow able to quantify things, we will get good management decisions.

• *Mr. McIntyre, McDonnell-Douglas Corporation:* I believe that it takes one or more teams to sell new concepts. First, it takes one group to assess the background and to develop an improved system. Quite often these technically competent people are not salesmen, and therefore lack the ability to sell the idea to the program managers. So they need to team up with someone who knows how to put it over, someone who can develop an innovative way of demonstrating, not simply describing, the value or utility of a device to the managers and the operational personnel.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* Stan has been talking about the technique of using blunders in evaluating equipment. Now there are many head-up devices in existence--Eliott's CFF, Sunstrand, Librascope, Norden, etc. Suppose we ran an evaluation of these different systems including the one proposed by CAPT DeCelles and the results showed that the blunder rate was higher with CAPT DeCelles' system than the others. Would CAPT DeCelles accept these findings?

• *CAPT DeCelles, Air Line Pilots Association:* Sure I would.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* These evaluations produce a lot of good, reliable, and suitable data; but somehow or other these data are not available when the decision takes place. Somehow the piloting job seems to require something more than raw objective data to convince the pilot to accept a new device. He must understand the thing, he must believe in it, and he must be willing to accept it. We might build a fly-by-wire system and sidestick controllers with all the reliability in the world, but if the pilot is not convinced, you are not going to put it in an aircraft. The change-over from air driven to electrical instruments is a good example of this point. Even when we knew the electrical instruments were highly reliable, and we could prove they were much more reliable than electrical instruments, pilots were still unwilling to accept them. So I suggest that the objective data are not sufficient. The pilot has got to have a gut belief in the new equipment, but your managers do not know how to give him this and that is why we are having trouble making these decisions.

I would like to make another point. It used to be that we could slap together some type of idea for an instrument, stick it in an airplane and go out and fly it. Then we could make any necessary changes in the display on the basis of observation and performance. Now, as you have heard in the papers presented today, we seem to be getting more into procedural techniques, and I feel that many people involved have not adapted to this change yet. Many of the people developing hardware come into our offices and ask what we need, but very often we do not have an answer for them. Time and effort are required to determine what kind of performance or display content is needed, and I think we must recognize this and change our methods. It is not just a matter of developing theory; a lot of work is going on in bits and pieces, but it must be coordinated. I believe that perhaps the best thing that will come from this meeting is that a lot of groups, who have felt that they had a handle on the problem and understood it, will recognize that other factions have other approaches. We have heard from the individual who is faced with the problem of developing and producing equipment within the limits of a rigid time schedule. We have heard from the individuals who are concerned with ivory tower theory development and the modeling techniques. All of these have to be brought together. I think another advantage of a meeting such as this is that it generates communication, which is terrifically valuable, but very difficult to achieve. So I think not only do we have problems in technology and methodology but we have the more difficult problem of keeping abreast of what is going on, and exchanging information. Many times we find work being done over and over again, simply because the people involved did not know the work had already been done.

• *Mr. Braid, Ferranti Ltd.:* We seem to be straying from what I thought was the intention of this conference--that is, to get the various groups interested in crew systems design together, rather than to separate them

as has been done. It seems to me that we should be trying to look at a cockpit, which after all is a piece of hardware, and see if we can't economize in design by not reinventing the wheel. So I would like to think that at this conference, while we have cockpit designers in other rooms, we might manage a displays and controls group to propose some standardization of units for cockpits.

• *Mr. Wolin, Naval Air Systems Command:* I do not feel that we have addressed ourselves to the items that were listed in the agenda. Many people in this group have been in the business a long time. We are acquainted with a lot of the work that has been done and, despite what others have said, we have made tremendous contributions in the last ten or 15 years. We were hoping we could assemble the experts and help the entire industry. So I was hoping, Jack, that you could redirect the formal speakers and those in the audience and try to fulfill the objectives stated in the conference announcement. You have the expertise right here if you can just get them to put pencil to paper.

• *CDR Hartranft, Naval Air Systems Command:* As a member of the JANAIR steering group committee, I would like to second Jack's comments. You have heard the comments made by individuals in the general assembly who get up and say we are talking about the same old problems over and over again. I suggest that we start listing these problems and then start generating some recommended solutions to them. This is the direction that all of the other workshops are taking. With all the talent we have here we must take the bull by the horns and come up with some recommended solutions.

• *Mr. Stanton, Jr., NASA Headquarters:* I was essentially going to say the same thing. My opening statement is "think positive." Obviously we have not done so today, and I am also disturbed about this. I am worried because most of the individuals here today, including myself, have been leeches--trying to suck things in, but not putting anything out. It is about time that we started to contribute. I suggest that when we convene tonight everyone think about what has gone on and attempt to write down some truly innovative ideas.

• *Mr. Wolin, Naval Air Systems Command:* I would like to make one more point. One extremely useful product that could result from this meeting is a list of the areas that we should be exploring. Dick Atkins pointed out the importance of gold. Those of us who have the gold are not going to give it to you unless you tell us precisely what should be explored. We are circulating a bibliography of all the research that has been supported by JANAIR since its inception nearly 20 years ago which will tell you what we have done, but now we need to know what areas we should explore in the future. I have heard a lot of complaining and criticizing here--in fact, I have heard human factors people criticizing each other. That is not what we are looking for. Human factors, systems engineering, and material science groups have all done some remarkable work for us. But now we want you to tell us positively what areas of exploration would be most fruitful in the future.

• *Mr. Hoerner, Naval Air Test Center:* The hardware that is coming along--plasma, LEDs, and so forth--is programmable. But we in the government do not have a specification for the display formats, we do not know what we want yet. But because of this very capability to reprogram in an airborne vehicle, we can go out and perform the test and evaluation to get the dynamics and the range you are looking for. I am proposing that with dedicated aircraft you will have the capability to examine the equipment, fly it, and look at all the software problems. You will then get an acceptability by the pilot community that you will never get when you release your contract in a smoke filled room when no one is there to really look at the system. With the generation of the displays available today, we can perform an iterative flight test program. So I am sorry Jack, it sounds like you were chasing us for not saying anything, and I thought we were saying very clearly that there is a way to develop crew stations and have a much better chance for success when the equipment finally gets into operational aircraft. Although this may not be the only way, it is a clear improvement over the present iterative process with aircraft with hard-wires memories.

• *Mr. Armstrong, Bunker-Ramo Corporation:* I have a couple of comments to make, possibly indicating a better way to get at the real-world situation. Nader has found many problems with the design of automobiles. The manufacturers of automobiles were probably aware of those problems many years ago, but they kept these problems under the rug because they would not sell automobiles. The same thing is happening in aviation and space technology. The people dealing with the displays and controls know the shortcomings and deficiencies, yet, they hide them because they know deficiencies may keep them from winning a proposal. We have to have a system whereby credit is given to people who identify the shortcomings of a system--a system that will also provide funding for needed improvements. Then test and evaluation will not have to go back and find out what the designers already know.

• *Mr. Suvada, Astronautics Corporation of America:* I think it would be beneficial

to hear positive approaches to the display problem. I am not here to solve operational problems, I am here to solve display problems and to try to offer constructive and positive recommendations on what can help me design a better instrument to display whatever the operational people want. I make a strong plea for consideration of the arrangement and the structure of the cockpit.

• *CDR Hartranft, Naval Air Systems Command:* I have heard very little discussion about the problems associated with the use of head-up displays in IFR conditions and have heard nothing at all about the problems associated with visually coupled displays. If these problems have been solved, we would certainly like to know about it.

• *Dr. Bernotat, Forschungsinstitut fur Anthropotechnik:* It seems to me that instead of attending to the improvement of very special equipment, our most important objective should be to try to improve our research and development tools. We can do this in different ways. First we could try to obtain a consensus as to which research methods are most useful at present. Second, we should get recommendations on improving research methods and criteria for the future, and also look at the problem of funding for this objective. I am quite sure that this could not be done in this group, but perhaps a regular working group could be set up to work toward meeting these objectives.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* One of the suggestions made was that the group should be identifying the specific hardware deficiencies or needs so that contracts can be developed to produce improvement in the crew station area. Another issue is that we have to have better ways of measuring performance and evaluating needs. The hardware issue is coming along but what to do with the hardware is not quite so clear. The operational people would just like to see what they need in the cockpit. We should start off by trying to identify the big issue or roadblock or whatever should be of prime concern to a group like this.

• *Mr. Hoerner, Naval Air Test Center:* I believe there is a consensus that display and control hardware is not the fundamental problem, and that we have some excellent new display/control concepts around today--for example, fly-by-wire, zero or neutral stability (stick steering auto pilots), and electro-optical display systems. In my opinion, the fundamental problem centers around the software used with these systems. Are we ready to attempt to standardize the size and location of cockpit displays and controls and to let the software determine the requirements of specific missions? If standardization is desired, how and when do we arrive at it?

• *Mr. Carel, Hughes Aircraft Company:* I would like to address the first question concerned with the standardization of displays. The electronic display is used not only for symbology but for sensors. Periodically the question arises as to whether we should standardize on a 525 line system of a particular size. But the sensor people continue to increase the resolution and field of view of the sensors--the FLIRS, the TVs, and the radars. If the viewer of these displays is to see the information the sensors are capable of resolving, then the display has to be matched not only to the capabilities of the sensor but to the capabilities of the operator as well. If we standardize on size, you are going to cut out new sensor developments right off the bat. I consider this to be one roadblock standing in the way of standardization.

• *Mr. Suvada, Astronautics Corporation of America:* I do not think we should attempt to standardize specific display characteristics such as the number of raster lines. Rather, I think we should attempt to standardize the broad classes of displays and their size. I think we should investigate the feasibility of having three basic types of displays: a vertical display, a horizontal display, and a control display unit. I believe we should also go one step further and tell the airframe design people that we need a minimum of 14 inches of depth behind the display panel for the instruments. Finally, I would like to point out that software programming is not only for the systems operational people. An additional software package can be associated with display management. How do you provide the flexibility for generating different types of displays, different types of symbology (be it raster or holographic)? There is a distinct advantage in having a software program for display management regardless of the operational requirements and the operational computer software programming that is located in different devices throughout the airplane.

• *Mr. Carel, Hughes Aircraft Company:* I am really not concerned about whether we are talking about cathode ray tubes, liquid crystals, or plasma displays. I am talking about the image the operator sees. If we settle on a size, we immediately limit the amount of information from the sensor that can be read out on that particular display. Therefore, I would hate to restrict ourselves to a five-by-seven display, regardless of the media, because the impact on sensor development would be just too great.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* The subject of standardization

has to be pinned down more specifically. We must define whether we intend to standardize on size, information content, resolution, etc. And if all of this is changing, perhaps attempting to standardize at this time would seriously interfere with progress. Perhaps all of you should submit your feelings in writing about whether or not we should attempt to standardize at this time, and if so, what should be standardized.

• *LCOL Madero, USAF Instrument Flight Center:* We are regularly involved in control, display, and guidance programs. Even though we are in the Air Training Command, we work routinely with the Systems Command for direction on control, display, and guidance problems. In the Air Training Command, we do have a reservoir of expertise with our instructors, students (and flight examiners), from all over the Air Force. We have been investigating pilot factors for about 12 years and have been dealing with such subjects as: control sharing, optimum display arrangements, low visibility investigations, head-up displays for low visibility, tape instruments, and experimental ADIs. I would like to discuss some of the deficiencies that we have noted in displays, controls, and guidance:

1. The first problem is the lack of standardization in instrument arrangement. We do have a military specification covering instrument arrangement, and we have instrument arrangements published in 5137, which is our instrument bible. However, it is very difficult to get people to use these standards.

2. A second problem is the lack of position information during approach, landing, and roll out under low-visibility conditions.

3. A third problem is the lack of good information on crab angle, which is especially critical in attempting to make an instrument approach with a strong crosswind.

4. A fourth problem is the lack of adequate systems failure information. Some of our flight director systems, for example, center out when they fail. There are no "off" flags, alarms, red lights, or any other indication that the device has failed. If one happens to be on centerline and on the glide slope when this happens, the results can be disastrous. We know of two aircraft that were lost because of this problem.

5. A fifth problem concerns deficiencies in the design of tape instruments. Although tapes may be the way to go, we have not been able to establish a definite advantage, and they are deficient when you get below 200 feet where you have little time to spend on your cross checks. A glance at a round dial gives you rapid information because of the position of the indicator; but you actually have to read tapes to get information. Possibly, color coding is the answer to this problem, but we do not yet know.

Next I would like to address some problems associated with head-up displays. Phase I of our investigation was conducted in VFR conditions with a PCI, a HUD that sits out on the nose of the aircraft. Although we made very good landings with the HUD, we found that instead of using the peripheral command indicator as a peripheral information source, we were using it as a primary information source and picking up other information peripherally. We found that we were not picking up enough pitch information peripherally (for flare). Lateral alignment looked good. We have a good feeling for when we cross the threshold so we know how far down the runway we are. However, we don't see the signs along the edge of the runway peripherally, so we do not know how far down the runway we are when we touch down. Another problem is that we do not see the crab anble with the HUD.

With another type of HUD, a columated display that sits directly in front of the pilot, we found that just a single bar for flight path angle to lead us to the touchdown point does not provide enough information. We find that we fly right through the flare point. Again, even though it is focused at infinity, we are not getting visual cues in the pitch axis to tell us when to quit flying the HUD and to go visual. Perhaps this is a training problem, but we certainly feel it needs more investigation.

Other problem areas associated with the HUD include: clutter, lighting--particularly at night, when the symbology blends in with the runway and approach lights--the dynamics in symbology, and finally the concept itself. If you are looking at the HUD to the extent that you are seeing only the HUD and not the outside visual cues, possibly the concept itself is suspect.

Although we have not yet documented this problem, we feel there are some vertical situation display and horizontal display problems. We have not seen one yet that didn't jitter so much that it caused eye fatigue. Although this may be a small engineering problem, it looks like a pretty big operational problem to us. There is also a problem with the failure in the backup systems for vertical situation displays and horizontal situation displays.

It seems apparent that we will need to

develop displays and controls for the microwave landing system which is programmed for the near future to replace the ILS. Since this system is programmed to go down to category 3C, we are certainly going to need some pretty sophisticated displays to support that particular system's development.

Flight instrument displays specifically designed for the helicopter and STOL are virtually non-existent. We are looking at the helicopter flight instrument envelope, and the helicopter pilots have responded to a survey by saying they are simply not flying instruments. They are sitting there with the old ID 249s, course indicators that were designed for fixed wing, and they would rather go below the weather (half-mile visibility) than try to keep their machine stable within the weather. So I think we are looking at a large void as far as control display development in the helicopter and STOL. I flew STOL for some time, and we never made an instrument approach in the STOL configuration. There just was not any system to allow us to.

I feel we need to take another serious look at the outside-in and inside-out concepts for attitude indication. I no longer think that this problem has been settled once and for all. Some of the younger pilots think the moving aircraft symbol on the A-7 head-up display is the greatest thing since canned beer. They have not been brainwashed like some of the older pilots.

This list of deficiencies is not by any means complete, but it does pinpoint some of the areas that we feel need immediate attention.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* Colonel, as a point of clarification, you said that you did not have crab information, and yet you stated that you had the difference between the runway heading and the aircraft heading.

• *LCOL Madero, USAF Instrument Flight Center:* We had the information but we could not see it. So evidently it was not displayed predominantly enough.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* So it was not a matter of the information not being there, it was simply not in the right form and in the right place.

• *LCOL Madero, USAF Instrument Flight Center:* Yes, that is right.

• *CAPT DeCelles, Air Line Pilots Association:* Was this heading and crab information presented on the head-up or the head-down display?

• *LCOL Madero, USAF Instrument Flight Center:* It was only on the head-down display. We were not using the head-up display for the category III evaluation at Dulles. As I said, the only information was the aircraft heading information on the HSI.

• *CAPT DeCelles, Air Line Pilots Association:* Colonel Madero and his group are truly the pioneers in the fields in which we are trying to operate. We realize the head-up display question has many aspects and that there is a great need for experimentation. We hope that our presentation yesterday will not leave anyone with the impression that we think we have all the answers or that the answers are readily available. We are calling for experimentation and human factors input, and we have specifically asked for the cooperation of the Air Force and from NASA Ames. Just one final note, the symbology that we advocated in our presentation is aimed at solving many of the problems that Colonel Madero mentioned, particularly the crab angle problem and the fixation problem. Another important problem is that pilots need better information about how much runway remains in the blind landing situation. The British have found that when the pilot gets on the ground and he can't see anything, he is tremendously concerned about how far he is from the end of the runway. We believe that it is not sufficient to simply tell a pilot how far he is from the end of the runway. He needs to know whether his present rate of deceleration is sufficient to stop on the runway. This is a fairly simple computation that can be made by computers given the proper data that can be presented to the pilot on the head-up display.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* Is there anyone who would like to address any of the problems that Colonel Madero has mentioned?

• *Mr. Armstrong, Bunker-Ramo Corporation:* I would like to discuss some of the observations we have made in evaluating the ADI. We found that when flying down at the minimums, the pilot's attention is focused at the intersection of the pitch and bank indication bars. Furthermore, the pilot's attention will be focused slightly to the right or left of this intersection point depending upon the type of supplementary information he is using--vertical velocity, for example. It has been believed that the pilot scans the entire panel and that the space a few inches below the ADI is a good place to put information, but under low-visibility conditions this is not true. The information must be located very near the center of the ADI. A similar problem exists with the HUD. The HUD is a three-dimensional instrument.

First, it becomes a flat plate for digital information, and then it is no better than a control panel. And when an aiming symbol that projects the view beyond the HUD gives the third dimension, the flat plate information is destroyed.

• *Mr. Moore-Searson, Marconi Elliott Avionics Ltd.:* I think that the landing problem with the HUD might be solved through the use of a velocity vector symbol to overcome the crab problem. The touchdown problem could probably be solved by using an autoflare computer driving the flight director symbol. This was in fact done at the DC-9 trials about five years ago.

• *Mr. Hoerner, Naval Air Test Center:* At the risk of repeating myself, these are software problems. The head-up display is an example of taking the sacred six and bringing them up front where we continue to accumulate but not integrate. We feel that the velocity vector is one of the best ways to provide integrated information. But none of this is a hardware problem. I still believe that we could define an area for a head-up display, an area for a vertical situation display, and an area for a horizontal display and consider these areas to be the pilot's "workshop." Perhaps we could move from there to solving the software problems whether the displays are CRTs, plasma, etc. All I wanted to do was to define the work station for the crew member.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* Would it be fair to say that you are proposing that the hardware technology can do virtually anything you want?

• *Mr. Hoerner, Naval Air Test Center:* Yes sir, I believe we are approaching that point.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* Who should deal with this problem? Is the instrument manufacturer who has previously just been building hardware now responsible for deciding what should appear on the display? Who *should* say what is going to appear on the display?

• *Mr. Hoerner, Naval Air Test Center:* This is where the purchaser, the government in my case, is woefully far behind. We do not know what we want. This is why we have to work with the operational people in gathering the flight performance data to see what does work so that we can turn this around and come up with a document that will state what we want. Then the software can be defined. The new military standard 884 is the Navy's first step toward a standard; the only trouble is that it has not been flown.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* I take it that you believe the consumers ought to have a dedicated aircraft to investigate these problems so they can specify what they want. Bill O'Donnell of NAVAIR SYSCOM, within the last two months, has published military specification D811641 for head-up display systems to be used for military application. It is unclassified and is obtainable. I think that will answer, to a great extent, a lot of the questions that have been brought up here. The problem boils down to a user definition of what must go into the display before the manufacturer can build it. You must go through a mission analysis, a definition of information requirements, for all modes of operation within that mission, and then you can put together your display format with a minimum of problems.

• *Mr. Gurman, Army Electronics Command:* I would like to make a cautionary note regarding Mr. O'Donnell's specification. It applies to fixed wing vehicles, so we should understand that it is not necessarily applicable to rotary wing aircraft.

• *Mr. Waruszewski, USAF Aeronautical Systems Division:* While we are on the subject of symbology, I would like to give you some background information on how the F-111 and the B-1 got their head-up display symbology. In the early days before the F-111 specifications were developed, a group of pilots and engineers met and decided what symbols they would like to put on the displays without any human factors testing, flight testing, or anything else. The problem with the F-111 was that the symbols were locked in concrete after we put them into the specifications. The only way to change them would have been through ECP action. As for the B-1, again a group of people got together about two months ago (Air Force pilots, SAC people, engineers) and selected the symbology. Fortunately this symbology was not locked in concrete, we agreed to simulate it and flight test it in a prototype model, so that the symbology can still be changed at a later date.

We recognize a problem with HUD symbology standardization. At Wright-Patterson we established a preliminary committee composed of representatives from all of the directorates and laboratories which met to respond to a TAC letter concerning symbology standardization for both head-down and head-up displays. We told AFSC, who had forwarded the TAC letter, that we do need concrete human factors analyses and testing to determine what symbols should be used. This information, we proposed, would be used to update 884B which, I feel, has not been adequately tested. We proposed studies on: font, line width, refresh rate, contrast,

recognition, symbol recognition under dynamic conditions, and so on. We have not received an answer from headquarters but I doubt they would fund such a program. The Navy does have a program to test the symbology on their A-6 display. They have procured a programmable symbol generator. I certainly think this is a step in the right direction. The 81641 symbology is based on flight test work that has been done previously with some experimental HUDs at Patuxent River and also considerable experience in the A-7E program. We feel that we are on very firm ground there, but with the A-6 programmable HUD, we feel we can investigate in considerable depth just the types of things you are talking about. The F-15 symbols are a combination of the F-111 and the A-7E symbols. These symbols were selected at a meeting and are somewhat locked in concrete; we are having a hard time changing them.

With reference to the standardization of display size, I am against any particular size being standardized. Right now, we are working on the B-1, the F-111, and the F-15 and some other special projects. And you can compute the optimal size of display on the basis of a 13° visual cone. When you are retrofitting an aircraft such as the F-4, these computations suggest that a 10- or 11-inch display would be optimal. But we have no data to determine how small the display can be and still be useful. I think we need some studies like this since you simply can't get a 10-inch diagonal screen into the cockpit of an F-4 and leave room for anything else. I think the function of the display will determine its size. If it is in the cockpit, and the pilot is using it as an EADI, he may not need as large a display as he would if other sensor data were going to appear on the display. It could be that two standard size displays will be required, one for flight information and the other for weapons delivery and sensor information.

• *Mr. Wolin, Naval Air Systems Command:* I would like to discuss a NAVAIR program that is concerned with the design of the total cockpit. This program, known as the aircraft integrated module instrumentation system (AIMIS), is a research and development program in which we have attempted to take into account the most up-to-date scientific technology. The aircraft concept is that of a carrier-based, all weather, attack-class aircraft that would meet requirements in 1980-85. Our scientific approach was to thoroughly define mission segments and also determine what information is required to accomplish each segment. The end product is a list of information required for the aircraft to accomplish its assigned mission or missions. We considered information for display, switches, caution lights, and so on. After considering technology in all the relevant disciplines, we decided that all the displays would be computer driven, but that the particular media would be undetermined for the time being. Recognizing the individual differences among pilots, both in abilities and preferences, we believe the display systems should be programmable not only to provide the information required for different missions, but also sufficiently flexible to accommodate these individual differences. We conceive of an integrated head-up display, an integrated multi-mode, multi-sensor head-down vertical situation display, and an integrated multi-mode horizontal situation display.

A number of problems have been encountered during this research and development program that I feel constitute specific challenges to the scientific and hardware communities. First, since all the displays will be computer driven and thus programmable, software is necessarily important. We will need more economical and timely techniques for programming the airborne computers. Second, since we conceive of multi-sensor displays, we must necessarily deal with the problem of interface. We believe that developing a means of presenting information from a variety of different sensors on a single display constitutes a tremendous interface problem. Third, we need a master monitor to display caution and advisory information, but development of such a display will require considerable research and development effort. And fourth, we need a master switch that will provide the pilot with efficient control in flight-mode selection and sensor selection.

We feel that these problems constitute a challenge for solid state physics, solid state chemistry, computer technology, and a number of other scientific disciplines in addition to the human factors specialists and hardware engineers who will eventually design the components. Also, successful completion of this program will require both ground-based simulation facilities and airborne simulation facilities in the form of a dedicated aircraft.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* I would like to pose a couple of questions that can be considered while we listen to other speakers. I wonder how you hardware manufacturers are going to deal with these big fancy systems when you can't make the present components work very long? How much good will putting a lot of flexible instruments in the cockpit do when the pilot has too much in the cockpit already? What good is standardization if you are going to have the flexibility that will enable each pilot to change the display to meet his particular preferences?

• *Mr. Kopchick, USAF Avionics Laboratory:* I agree that software, not hardware is going to improve the performance of the crew. But we have to get smart about how we incorporate software. We are not going to improve systems performance by thinking of subsystem software, we have to start thinking in terms of the total system. Although we are firm believers in some of the advanced display concepts, I think questions concerning standardization and the need for head-up displays can be answered only after we have looked at the total system. This information should dictate the need for standardization, head-up displays, and so on. Before attempting to standardize, we should establish commonality across aircraft types and across missions. I believe that hardware problems, such as reliability, will be easily surmounted in the future. The real challenge lies in how you put the system together. I would like to refer you to the article in a recent issue of *Aviation Week* that describes our approach. The title of the article is "Integrated Digital Avionics."

• *Dr. Hunt, Royal Aircraft Establishment:* First, concerning the issue of customer and industry responsibility for deciding what displays are wanted, we at REA think this is highly complex and that we all have a role to play. We see ourselves as the link between the manufacturer and the services because we have tremendous expertise, facilities, and equipment, including simulators and aircraft that are absolutely essential to this role. We can, therefore, evaluate available equipment and try to match what industry is producing with the requirements that our services give us.

In regard to the role of the dedicated aircraft, we have developed head-up displays for military and civilian aircraft over a considerable period, and we have found dedicated aircraft essential for working out both software and hardware problems. The Tripartite program is another example of the use of dedicated aircraft for specific problems--again, both software and hardware problems. I think the apparent consensus of this meeting that hardware problems are declining in importance while software problems are becoming more apparent, is generally true. However, I also observe that modern electronic displays still have an enormous number of unsolved hardware problems. You can almost certainly find fault with any piece of equipment. Even those head-up displays that have been around for some time still have substantial hardware deficiencies, if not problems. I think some of the deficiencies are: they are too cumbersome, they intrude into the cockpit space, they have limited field of view, they are almost invariably monochrome, and their brightness is not adequate. And almost any other area--head-down CRTs, plasma, liquid crystal, LEDs--will show hardware deficiencies that make our job of selling modern displays to the pilot community much more difficult. Although tremendous strides have been made in hardware, we still have a long way to go. I think there are real dangers in attempting to standardize at this time, simply because the field is evolving at such a rapid rate. I do agree, however, that there is also an enormous amount of work to be done on software.

One final comment concerns flexible electronic displays. We are doing a great deal of work in the United Kingdom on flexible electronic displays, and we are starting out some flight evaluation of these head-down in the very near future. One of the most frequently mentioned "advantages" of electronic head-down displays is flexibility. I concede that this could be a considerable advantage since: it may save space and pilot strain, he can select whatever parameters he wants, and the pilot's scan pattern does not have to be distorted because he has to read a vast number of different instruments just to get a small amount of information. However, I am seriously concerned about the possibilities of misreading or blunder if the pilot happens to set up the wrong modes on the display so that he thinks he is reading engine pressure ratio when in fact he is reading something altogether different. So I would like to know whether the people here think that we can sufficiently protect the pilot from making this sort of blunder.

• *Mr. Mueller, Army Aviation Systems Command:* I am glad to hear that the people in the Air Force and Navy have solved their hardware problems. Unfortunately, in the Army we still have basic reliability problems. We cannot get instruments that will last any time at all in a helicopter environment. Perhaps because we try to adapt fixed-wing aircraft instruments to helicopter environments where the instruments are submitted to a great deal more vibration and dirt. Unfortunately, I think we are perpetuating this problem in our second generation helicopters. As far as I know, no effort is being expended in developing instruments that will survive in a helicopter environment, but we certainly need it.

I have two questions. What is being done in the area of wide field-of-view displays--i.e., between 90 and 130 degrees? Has anyone done any work to define how much peripheral field of view is useful to the pilot in low-level operations?

• *Dr. Fenwick, Collins Radio Company:* As a representative of an instrument manufacturer, it is my opinion that the problem of instrument reliability is more a function of the nature of the procurement process than it

is a technical problem. But I agree with Mr. Wolin that if we are going to accomplish anything worthwhile we should identify the kinds of things that his organization and others should be doing to solve the problems. I have some recommendations I would like to present, but before doing so I should explain the assumptions which underlie these recommendations.

The determination of control and display requirements is essentially a deductive process which begins with mission requirements, is bounded by roles assigned to the crew, and reflects the known strengths and limitations of humans in such roles. Since the human's transfer functions in the operation of complex systems are known only in gross terms, it is unrealistic to expect that we can reduce the control and display conceptualization process to a set of procedures. Defined mission requirements and established crew roles serve to bound a solution base that can be filled only through the process of invention. To a large extent, every combination of vehicle, mission and crew roles presents a unique problem of crew station design. The ultimate criterion against which this process of invention must be assessed is probability of crew blunders during system operation. But since no objective means are available for assessing the effectiveness of a complex man/machine interaction against such a criterion as blunder proneness it is not surprising that project managers emphasize system attributes that can be more readily assessed for compliance with vehicle mission objectives. And this is one reason behind a trend toward increasing automation in vehicle control and information management systems. When we specify for example that an aircraft should be designed to a certain safety in landing, the engineering disciplines can meet this requirement because the integrity of the system can be modeled. But if a man is a significant element in the process, confidence in the model necessarily suffers. Therefore I submit that the methodologies we must adopt and perfect in crew systems design for the foreseeable future must be more managerial than technical in nature. We must learn to accept and exploit the fact that these activities are critically dependent upon expert judgment derived from a wide variety of experimental backgrounds and points of view.

To JANAIR concerning the types of research that should be supported, I suggest a reduced emphasis on development of methodology and an increased emphasis on empirical examination of some central, very practical, issues in crew station design that will be presenting designers with countless dilemmas in the years ahead. First, and somewhat implicit in a lot of what we have been hearing the last couple of days, has to do with the allowable limit of time sharing of control and displays. It will become more and more apparent in the next few years that time sharing on multi-function electronic displays can be carried to absurd extremes, and yet the experimental literature has very little to offer on what the boundaries of this might be. Second we need to know more about the general types of tasks that human operators are good at and not so good at, as revealed, perhaps, by thorough examination of accident reports from the aviation history. Extended further this work would attempt to relate accident records to specific design features of different vehicle types. Third, what possible problems are created by over-automation of a vehicle's operation and monitoring wherein there are insufficient forces to activate and direct the crew's awareness? And fourth, how does stress affect pilots' performance and what implications do the effect of stress have on training practices. Finally, I think the nature of the crew station design process itself is an appropriate object of study. Such a study should aim at developing recommendations that are as much managerial as technical.

Now one last remark I can't resist making. We have heard some suggestions here to the effect that one can design displays so thoroughly flexible that the process of adapting them to a given set of functional requirements is reduced to software development. In my opinion this assertion about the state of the art of display device technology is utterly fallacious.

• *CAPT DeCelles, Air Line Pilots Association:* It should be kept in mind that the pilots an airline company sends to a working session are a certain breed of cat. Although these representatives are honorable and capable, they have a particular point of view which, in many cases, does not represent the point of view of the majority of line pilots. I think there is a bit of difference between the pilot who has gravitated to a desk and is doing all his flying there and the guy who is out in the grime and dirt flying these airplanes under tough line conditions.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* Assessing pilots' opinions poses some problem. You certainly can't take a vote from all of them, and I do not know how you select the most representative. In our experience, when you get a line pilot involved in design problems he becomes educated and because of this education, he is no longer representative of the population of line pilots.

• *CAPT Hawkins, KLM Royal Dutch Airlines:* I would like to correct any misunderstanding that may have arisen from CAPT DeCelles' comments about engineering pilots who represent airlines and manufacturers. In many projects here and in Europe, the engineering pilots concerned all continue to spend time as line pilots. In many projects, all of the engineering pilots spend 50 percent of their time as normal operating line pilots.

• *Mr. Baumunk, McDonnell-Douglas Corporation:* I would like to make some comments from a designer's point of view. Although the objectives of this meeting encompass both the development and evaluation of displays and controls, I do not feel qualified to discuss evaluation and will limit myself to the design process. Three basic components enter into the design of aircraft instruments, cockpits, and the whole aircraft. The first component I call the user--Army, Navy, Air Force, the airlines, and so on. The second component is the assembler, the aircraft company. The third component I refer to as the subsystem supplier. We can call them vendors or manufacturers, but a subsystem supplier is sometimes the user in the sense that he supplies GFE equipment. The subsystem supplier can also be the aircraft manufacturer who designs and installs his own subsystems. My points will be made within this context.

My first point concerns information the designer needs to integrate the displays and controls into the total cockpit design. This integration includes: designing some of the displays and controls; specifying the requirements for the displays and controls that are to be procured or supplied by the user; coordinating the procurement process; and arranging and installing all the displays and controls. The next question is, what can I do to help the user in his task, to help the supplier in his task, and to assure my company and the user that I can design the total cockpit to meet their requirements?

I need to know the user's operational objectives and requirements, both desired and minimum requirements. I need this information not only for the first series of aircraft to be procured, but also for future aircraft series, when aircraft use may differ. Without this information about potential future uses, it is impossible to provide for future growth or modification.

I need to know the workload capabilities of the crew and how workload is affected by conventional as well as more advanced and sophisticated equipment. I need this information for both normal and abnormal operating conditions.

I also need to know the state of the art of controls and displays, the suppliers' capabilities (off-the-shelf and developmental), and what I can design and develop within my assigned time schedule.

Now, what can I do to help the user? I can tell him what we have done and what I know we can do. That is, I can define our technical capabilities and limitations to help the user tell me what he would like in the airplane. I need to tell the user what we know about the ramifications of cockpit design, such as size of the cockpit, space, weight, cost, performance, and payload as affected by the displays and controls. Finally, I would tell the user what we are doing, what we plan to do, and what we would like to do if we had the wherewithal to advance our capabilities if it appears necessary to meet the user's upcoming objectives.

What can we do to help the supplier? We can inform the supplier of display/control requirements that can be met more effectively by him than by the aircraft manufacturers. We can tell him the space and the size limitations and the ramifications. And we can tell him where we think he should advance his technology and capabilities.

Apparently, the key point in all of this is knowing the user's objectives and requirements in terms of his cost effectiveness. My major recommendation is for more direct research into the operational advantages and limitations of advanced instruments and displays.

• *Mr. Braid, Ferranti Ltd.:* To follow up my statements, and because of the adverse reaction a number of individuals had to the word standardization, I wish to make a plea for a better definition of which parameters of the electronic displays could and should be standardized now and which should be standardized in the future. My personal opinion is that considerable advantages could be gained by standardizing now on a range of front-mounting panel dimensions for the boxes and fixing screw details in a fashion similar to the standardization that has already taken place in control units on military aircraft and, in the case of civil aviation, displays as well. Even without any standardization of the depth of the box at this stage, a range of standard front panels would assist both the cockpit designer and the equipment designer, while also satisfying the human factors requirements. It would save a considerable amount of effort and money. What may not be generally realized is that cathode ray tubes are considerably standardized already in facial dimensions. It would not be difficult to select a range of box-front dimensions to suit selected cathode ray tubes. By that, I mean we may go up in one-inch steps or two-inch

steps by agreement. What is even more important is that if we do not produce a list of box-panel dimensions now, the LEDs, gas plasma panels, and all the other flat plate devices are going to grow in a vast variety of sizes, dimensions, and ratios. If we could at this stage come up with a range of box dimensions to suit cathode ray tubes, the people developing flat plate devices may use the same dimensions and allow interchangeability and retrofit replacement at the later stage without upsetting cockpit designers. Quite a lot of money is going into the preparation of tools for these new devices, and none of us knows what is going to be the winning device in the long run for any particular application. If they are at least all made to the same dimensions, there is a possibility of using the best and having the best of both worlds.

• *Mr. Kearns, USAF Flight Dynamics Laboratory:* There were many negative comments early in the session, and some people were distressed by this negativism. However, as research people, I think it is our responsibility to look at the negative side, because you can only improve by knowing what is wrong.

There is a variety of types of people involved in the design and evaluation of crew stations. One of the things that I have observed many times in the past is that each of these types has a rather supercillious attitude in looking at the others. It is the attitude that I am doing what is important and the other guys are just playing around. To end on a positive note I think this meeting is evidence that we no longer have this type of isolation, it is gradually changing. It is in evidence here, a wide variety of types of people are talking together, not only at the meeting, but during the coffee breaks. I am very encouraged to see that many of these types are displaying an awareness that the other guy does know something and that it is useful to exchange information and views.

WORKSHOP SUMMARY

Mr. Kearns, USAF Flight Dynamics Laboratory: This was the largest workshop, and for good reason. The scope of our subject is large and our problem area is highly complex. The large number of people who attended this workshop gives evidence of the broad concern for controls and displays in crew system design.

Ordinarily, when people speak of controls and displays they are thinking of a collection of gadgets. But, this workshop demonstrated that there is far more to it than just gadgets. The participants were concerned with solving problems and with achieving specific objectives of crew performance. They represented a great diversity of interests and motivations. They spoke from the viewpoints of the researcher, the developer, the manufacturer, and the user--the pilot himself. But, in spite of these differences in point of view, they affirmed that controls and displays are, in a sense, the heart of the crew station.

Initially, our attempts to cope with the totality of the problem produced a great deal of frustration, which I think reflects the concern that gave rise to this conference in the first place. Examples of new system concepts were proposed and considerable data were presented, but the users were not satisfied. Theoretical concepts or potential solutions were proposed and were greeted with cries of "Where's your data?" There was an inconsistency of griping for solutions and resistance to considering them. I think this occurred not because people are illogical, but because of the frustrating scope and complexity of our subject. One of the effects of this discussion was that interdisciplinary communication became, in the end, as prominent a subject as controls and displays.

When we addressed the question of how to bring about improvements in controls and displays in aircraft cockpits, many problems and issues were presented. We reached no consensus on these matters. Perhaps it is not to be expected that so many people with such divergent interests could reach a few simple conclusions.

Despite their divergent views, the workshop participants recognized that *something* must eventually be put into the cockpit and a pilot is going to have to fly with it, so it must be usable. Because of this fact of life, the discussion turned from the methodological and theoretical to the empirical and pragmatic. For example, there was concern for such matters as the reliability of instruments. They fail; and some fail all too early in their life.

There was increasing concern for software problems as opposed to hardware problems; not software in the sense of computer programming, but software in the sense of the information displayed and the operations or applications of the controls. Which should be the prime issue for control/display designers: the hardware or the software? If there is a consensus, apparently it is that we are transitioning from a principal concern with the purely hardware or engineering part of the problem to a principal concern with the application--or software--part of the problem. In this transition to a concern for software, somebody has to decide what information is going to be presented on displays and how it is going to be presented; how controls are going to move; how controls and displays will relate to each other, and like matters. Who has the responsibility for doing this? There are various possibilities. One is the vendor, the guy who has been making these instruments all along. Another is the customer or user. Perhaps a third is a group consisting of engineers, pilots, and other specialists.

Strong arguments were presented for the use of large teams wherein all the relevant specialties are collectively represented. Along with these arguments was a concern for how requirements and responsibilities are, or should be, established. Again, we had differences of opinion. The gut feeling, perhaps based on emotionalism, seemed to be that the pilot should have a dominant role in the decision-making process. If so, he has to do some learning. He has to do some digging to find out about the critical technologies.

Strong proponents spoke out for the dedicated aircraft and other tools to be used by the customer to determine his own requirements and to better convey those requirements to the people who will develop or manufacture the equipment, to more exactly define what it is that the equipment must do.

Consideration was given to the procedure by which improvements are authorized or changes instituted. There was not much argument on this point. The workshop participants seemed to recognize profit as the primary motivating factor. You can get almost anything done if you can prove to the guy who is paying the bills that he is going to show a profit for it. In dealing with this area of concern, it was clear that software improvements can suffer because the payoff can be intangible, or at least very difficult to pin down. For example, arguments for a particular system of HUD symbology can seldom be presented in terms of quantitative statements of requirements or benefits. In all likelihood

this situation will continue for many years.

Out of this limitation in our ability to present quantitative, profit-oriented evidence of requirements came the argument that emotionalism may be, after all, a necessary ingredient in selling an idea or in gaining support for a change in the crew system. It has even been suggested that perhaps the best opportunity for getting a change implemented is when a tragedy strikes. Then the higher authorities will listen, and the lack of quantitative evidence or justification is not going to be a detriment.

While there was a strong argument for the "total systems approach," there was no consensus on what constitutes that approach. Discussions centered on the development of total avionics systems which are based on computers linked to highly flexible electronic displays. But such systems pose problems that we have never encountered before: the demands placed on the pilot to call up the information he wants to see, to select from a variety of displays, to understand switching logics, and so forth. Concern was also expressed for the reliability of these sophisticated systems.

Army representatives stressed that the control/display problem in rotary-wing aircraft is severe and not adequately supported. That is, rotary-wing operators are forced to use instruments that were basically developed for fixed-wing applications and they find these instruments inadequate or unsuitable to their job. They pointed out that control/display reliability is an even greater problem in the helicopter environment. Apparently, some instruments literally shake apart.

Head-up displays came in for quite a bit of discussion, but no absolute conclusions were reached concerning whether or not they are needed or desired. The greatest deficiency seems to be the lack of an adequate test program to determine the most effective HUD design for different applications. The validity of the basic HUD concept--that the pilot can derive information from the HUD while he focuses his attention on the visual cues in the real world--was questioned. Recent flight tests seem to show that this just is not true. At least in some instances, particularly during approach and landing, the pilot finds himself focusing his attention on the HUD information while the real-world cues become peripheral to his perception.

Of great concern to the pilots in our group was the subject of landing, particularly under bad weather conditions or zero-zero visibility. The question is: what information do you display and how do you display it? From the pilot's viewpoint, such matters as the display of crab information and positional information on rollout become crucial. The key issue is not whether the information is available somewhere in the cockpit, but whether it is available where and when he needs it.

The adequacy of failure warning systems was discussed. A typical problem was the flight director: when it fails, the needles go to the zero or center position as though everything were fine. The subject of instrument failure warning caused concern for many years, and the problems are still with us.

Advanced display concepts that have been presented almost as panaceas were shown to have serious limitations: tape displays are inadequate in low-level flight, according to pilots who have flown with them. Electronic displays jitter and are hard to watch over a long period of time. With the advent of the HUD, the old problem of the outside-in versus the inside-out display format rises anew.

In conclusion, while we did not reach any consensus of views, the concern for the role of controls and displays in crew system design was intense. The impression that came through as strongly as any is that each of the parochial groups represented in our workshop developed a better appreciation for the existence and viewpoints of the other groups. Not just an appreciation was developed, but a desire to interface with these other groups and to exchange information. So, while we cannot present specific findings and recommendations to the conference at large, perhaps the greater good is that our workshop has recognized that many disciplines and interests must be brought together to deal adequately with the problems of crew system design.

ILLUMINATION AND LIGHTING IN CREW SYSTEM DESIGN

SECTION VII

AN IN-DEPTH LOOK AT TODAY'S AEROSPACE VEHICLE CREW STATION LIGHTING

MR. GEORGE W. GODFREY
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Abstract: *A review of the history of aerospace vehicle crew station illumination and how it has evolved is thoroughly discussed. The present status of all types and technologies of aerospace vehicle crew station illumination is also discussed. Further, an overall system approach is discussed in depth. Each of the five major subsystems is dealt with individually, on the basis of its merit. The responsibilities and other factors which have a tendency to degrade aerospace crew station lighting are dealt with very critically since the author feels that anyone can "throw roses." Basic fundamentals of design and techniques are not covered, but a referenced textbook is cited for this information. It is felt that an overview paper should cover the overall concepts and philosophies which would be more pertinent than design criteria.*

INTRODUCTION

Crew station illumination has followed a slow but steady rate of progress during the evolution of aerospace vehicles. During these years pilots, illumination engineers, psychologists, and others have made serious efforts to convince the manufacturers of these air vehicles to adjust the concept of crew station illumination to the needs of the flight crew members, rather than to place illumination last on the agenda for improvement. Or, as it has been said, manufacturers and management consider crew station illumination as a necessary evil, which is added after the crew station is designed and all other instruments, panels, and equipments are located.

The fact that there are so many factors involved in crew station illumination combined with the great amount of ignorance that surrounds it by those who are unfortunately unaware of their ignorance is the greatest single deterrent to good crew station illumination. This is not ignorance in its usual sense, but is the result of decisions by management, psychologists, and engineers who really do not understand the problem of the flight crew member nor do they have a good basic understanding of the physics of light.

However, those of us who have spent the last 20 years in this field will continue to persevere and, it is hoped, will continue to make progress. We feel that although laboratory testing is valid and necessary, the following still establish the requirements: the pilot who has to make frequent trips to downtown Hanoi at one o'clock in the morning to be greeted by a sky full of SAMs; the commander of a C-141 and its copilot who fly the Pacific nonstop from Alaska to find a 100-foot ceiling with quarter-mile visibility and rain and smog and smoke when they land at Yakota, Japan, in the middle of the night; the airline captain who must land at Los Angeles International Airport in darkness and smog so thick that he cannot see to taxi to the terminal. It seems logical that these are the gentlemen who must be satisfied, but according to a recent U. S. Air Force survey, these people are still not being listened to.

HISTORY

As far back as 1923, the British investigated, on a scientific basis, the requirements for maintaining maximum dark adaptation in an airplane cockpit, while still illuminating the cockpit instruments and switches. Apparently this investigation was too far ahead of its time, because very

little was accomplished. Indirect lighting (lamps installed behind a cover panel) was available back in 1934. Mr. John Bartelt, who at that time was at The National Bureau of Standards, was assigned to develop such a system. However, the demand for cheap and simple lighting led to the development of small cockpit floodlights, which actually did an adequate job of illumination if they were located correctly. But, as you all know, lighting has always been given low priority; other items of equipment in the cockpit were always placed first. Thus, the floodlight was located in such a place that it did not in many cases illuminate its intended area adequately and invariably caused glare and reflections.

During the late 1930s the fluorescent lamp was utilized to make ultraviolet lighting practicable. The Air Force (then the Army Air Corps) pioneered in the development of small 6- and 9-watt tubular light fixtures. This ultraviolet lighting technique offered glare-free cockpit lighting and high contrast, and seemed to be the ultimate in lighting. The small, RF-12, 38-volt, d.c., ultraviolet lamp became available and the Navy and Army both adopted it as a standard for cockpit lighting.

However, during World War II, when the B-17, B-24, and B-29 bombers were sent day after day on long missions, many of which exceeded 15 hours, the ultraviolet lighting system proved totally inadequate. It was found that while ultraviolet made spectacular darkroom demonstrations, it was impossible to live with in a cockpit illuminated in this manner over these long periods of time. Both direct and reflected ultraviolet in the cockpit caused the pilot's eyes to fluoresce, causing severe discomfort. Another severe problem with this system was caused by the ultraviolet light only illuminating the phosphorescent indicia on the instruments and controls and thus, there was no relationship between these indicia and anything else in the cockpit, and the psychological illusion of "floating" was created. In other words, the instrument appeared to move around in the instrument panel. For those of you who are not familiar with this method, the total cockpit illumination consisted of all instrument indicia being applied with some type of phosphorescent paint and ultraviolet fluorides being placed around the cockpit in such a manner that it energized these indicia and they glowed brilliantly in the dark.

During this period, Hartline startled the entire industry in 1941 by advocating red light for airplane cockpits. A demonstration panel which duplicated the ultraviolet panels was constructed with incandescent lamps and red filters, set up in the Navy Bureau of Aeronautics, and observed by many Navy officers. The red lighting was judged superior and the Navy decided to provide red lighting for night aircraft. Eventually, red lighting was adopted in all naval aircraft. The Navy used the indirect, or cover panel, system which was developed by the Navy during and after World War II. The principal difficulty proved to be the need for tailoring the cover panel to the instrument panel and the extreme accuracy required to prevent shadows and glare. This was solved when the Grimes Manufacturing Company developed the "eyebrow" light fixture. The development of plastic lighting plates carried effective red lighting to the consoles and control panels. The U. S. Navy and U. S. Air Force together conducted an evaluation to gather opinions from Navy and Air Force pilots on their subjective preference for the red lighting and ultraviolet lighting systems in the fall of 1949. As a result of this subjective evaluation, the red lighting system became standard for both services.

PRESENT STATUS

In the development of improved cockpit lighting systems for aircraft, the major goal is to enhance pilot performance. Two major but conflicting requirements must be accomplished in fulfilling this task. First, the indicia on the instruments and control panels must be made sufficiently visible so that the pilots' activities may be carried out with adequate speed and accuracy. The second requirement is that, where operationally necessary, the brightness of the lighting shall not interfere with the maximum obtainable dark adaptation.

Presently there is considerable conflict as to how this can be best attained:

- The U. S. Navy maintains that the best cockpit lighting system should utilize red light with a cutoff of about 600 to 620 nanometers.
- The U. S. Air Force maintains that the best system for cockpit lighting is to utilize what has been commonly termed "Air Force white" light. This is the normal incandescent lamp using a blue filter to keep the light from becoming yellow when dimmed.
- Most commercial airlines use white unfiltered light which allows the color to cover quite a wide spectrum.
- NASA for space flights specified a color spectrum of white light that is totally different from the Air

Force or commercial airlines.

- Private and executive aircraft use just about every type of cockpit lighting imaginable, and the sole basis is economic.

Therefore, as can be readily judged, each type of lighting being used has been "scientifically" designed and their developers maintain that it is the "only way" to do the job. And each developer has much scientific data to prove the advantages of any given lighting system.

A very knowledgeable test pilot, Mr. John Moore, once said that: "It is acknowledged that crew station lighting today is a science, and that sufficient data has been accrued from doctors, flight psychologists, physicists, and case histories to allow the illumination engineer to do a good job illuminating any given space. While armed with this knowledge the crew station illumination engineer can produce an artful job of illuminating the crew station to meet almost any specification. Nonetheless, the artist/scientist/illumination engineer must subject the fruits of his work to the flight crew member for whom it is intended. How often have these flight crew members' suggestions and criticisms of crew station lighting mockups been countered by, 'That's merely his opinion. There are no scientific considerations in a flight crew member's comments and the crew station lighting mockup meets all specifications.' However, it must be kept in mind that crew station illumination is designed for the flight crew member who uses it, not for the slide rule that calculated it." Until this is firmly understood, the one and only standard light fixture in *all* cockpits and crew stations will be the "flashlight."

SYSTEM APPROACH

The requirements for illumination of the controls, displays, and indicia in today's aerospace vehicle call for a highly scientific approach. The fact that the aerospace industry is placing the greatest demand on the illumination engineer for new techniques and better lighting emphasizes the necessity for constant development to keep pace with the ever-progressing aerospace industry. Aerospace lighting is of necessity a highly specialized field. Unique conditions require a sound knowledge of the physics of light and optics. Further, a complete knowledge of the crew station configuration and its utilization and the crew member's task is a must. The characteristics of these crew stations are constantly changing and with them change the lighting requirements. Certain statistics may be helpful to point out the magnitude of the job of lighting one of today's high-performance aircraft. The average twin-engine, two-place, high-speed, military aircraft has approximately 500 specially designed lamp installations using every known optics technique. Most commercial transports use several times this number of lamps. This lighting, and the system necessary to make it function properly, can use 2,000 watts of electrical power--more than the entire electrical system on a World War II aircraft.

It would be impossible for me to try to explain within the short period that I have available for this presentation the vast technology that one is required to understand to deal adequately with crew station illumination. This is contained in a book entitled *Principles of Display Illumination Techniques for Aerospace Vehicle Crew Stations*, and can be obtained from the address shown in the References section of this paper.

Before any individual design can begin on instruments, control panels, warning/caution indicating systems, special displays, floodlighting, etc., an overall and homogenous crew station illumination system concept must be derived. After this concept is developed, a fully functional accurately configured, lighting mockup of a particular crew station, using correct canopies, windshields, side windows, etc., with the same quality of optical characteristics that will be used in production must be fabricated. This should be accomplished prior to freezing the design of the individual lighted components, but invariably this does not happen. Lighted mockups normally are fabricated using the prototype hardware of the first production run. Therefore, needed corrections in design, when found during the lighted mockup review, cannot be corrected because of the economic and schedule impact on the vehicle production. Thus, from the time the first vehicle rolls off the production line until, in most cases, many years later a given air vehicle suffers from bad design in its crew station lighting system, the crew members must tolerate this inadequate and quite often unsafe condition. As mentioned earlier, most often this mistake is caused by management and procurement service allegiance to economics, and individual ignorance, rather than by lack of design technology.

TYPES OF CREW STATION ILLUMINATION

Crew station illumination can be divided into five basic types, each of which may be designed separately but must be compatible with and complement the other: (1) instrument lighting, (2) lighted control

panels, (3) cockpit floodlighting, (4) enunciator panel lighting, and (5) special displays that emit light, such as CRTs (both TV and radar) and head-up displays.

INSTRUMENT LIGHTING

Instrument lighting, or display lighting, has probably reached the highest degree of engineering of any type illuminating technique utilized in a crew station. Many special light sources have been developed for this purpose, analytical formulas derived, optical wedges and transillumination techniques perfected, which allow the illumination engineer to light a given instrument or display in just about any manner that specifications require.

One of today's problems is that, as mentioned earlier, different services and different types of vehicles specify different types of instrument illumination. Thus, standardization is not utilized when actually it should be the prime factor in the design. This not only is tactically wrong, it is economically expensive. This particular problem could be resolved by conferences of all parties concerned held by knowledgeable men with open minds.

The part of instrument illumination that is the most critical problem in today's crew station is illumination balance, or the evenness of illumination of all instruments on a panel. Cockpit illumination must be engineered so that it provides a crew member with a wide variation in intensity and enables the crew member to cope with the various situations on a given mission. As the ambient illumination outside a crew station is decreased until it approaches total darkness, the crew member will gradually reduce the intensity of his instrument illumination, often obtaining extremely low illumination settings so that he can perform his task while maintaining his night vision. This will continue to be a requirement until complete automation has been accomplished in the control of take off, cruise, and landing. Regardless of whether this illumination is red, white, ultraviolet or any other color, evenness of illumination is a must under any one of these lighting systems. Since a crew member cannot see what he cannot see, he has a tendency, when his night vision is reduced, to proceed blithely on like a turtle with his head withdrawn, assuming that since he has not run into anything yet, he probably will not. This, of course, does not promote safety of flight. Although positive control of all aircraft in conjested areas at night has become almost universally prevalent, one need only take off or land an airplane at Washington National Airport to be keenly aware of the sensation that he closely resembles a bee departing from or returning to his hive. The importance of good night vision under these circumstances cannot be overstated.

The adverse affects of unbalanced instrument lighting, as with most lighting defects, are primarily psychological. That instrument which has a higher intensity of illumination than the others is quite irritating to a busy crew member, and to alleviate this condition the usual practice is to turn down the intensity of the brighter light until it is no longer uncomfortable, which will result in other instruments being inadequately illuminated. This, of course, can create a safety problem caused by his possible inability to interpret a given instrument correctly. I cannot overemphasize the fact that this particular problem is more critical than whether to use white, red, or any other color light; and, yet, in all probability 90 percent of air vehicles have this condition. As one pilot noted, "Very little can be done about this, so pilots put up with it--in much the same way they put up with grumpy wives and two-year-old sports cars."

LIGHTED CONTROL PANELS

The state of the art of controls and control panel illumination has improved in the last 15 years until at present it is probably the most satisfactory system of illumination in any crew station. Uneven illumination of these controls very seldom affects a crew member (unless, of course, the unevenness is so gross that it would not satisfy specifications). Stroke-width-to-height ratio of indicia, the placement of indicia, the illumination of switch handles, knobs, etc., have been perfected very satisfactorily and are being applied quite uniformly.

One problem still exists which is caused, for the most part, by the ignorance of the engineer charged with illumination of a given control panel: the placement of digital readouts or gauges on a horizontal console would be, as the modern mother would explain it, a "no-no." This does not mean that the illumination design engineer cannot illuminate digital readouts or gauges on console control heads to meet the proper specification; he can. However, when these particular control heads are installed incorrectly in an aerospace vehicle crew station, it is impossible to keep stray and reflected light from these devices from being reflected in canopies, windscreens and side windows. These reflections are probably the most dangerous phenomena that a crew member must tolerate. This is caused by the fact that the particular location of the reflected light in the windscreen or canopy moves as the crew member moves his head; and

since it is a necessity to "rubber neck" (keep a constant lookout for other aircraft), quite often this reflected light can be mistaken for the anti-collision light of another vehicle. To determine if it is an anti-collision light or is reflected light requires time, which quite often is not available for that purpose. However, this determination must be made because as one airline captain very aptly put it, "A mid-air collision can ruin your whole evening."

COCKPIT FLOODLIGHTING

General illumination in a crew station, or so-called "floodlighting," not only is a specification requirement for most air vehicles but is a must for proper design of the entire space. There is an old adage which states, "If you do not light it, do not install it." This particular rule is violated often, because without exception you can get into any crew station and find item after item that has absolutely no means of being illuminated, except by a flashlight.

Secondly, this method of illuminating is normally used as a backup or emergency illumination in the event of power failure and therefore should be designed to allow safe operation of the air vehicle in the event the primary system is not available. It should provide adequate, even illumination from a very low level of intensity to extremely high levels of intensity. This is required because during normal operation of the primary system of illuminating instruments and control panels, the floodlighting is used at an extremely low level to orient and identify all fixtures within the crew station. However, when proceeding through a thunderstorm or during dusk or early morning sunrise --very similar to driving an automobile--the ambient light is not sufficient and must be supplemented by floodlighting in order to satisfy the visual requirements of safe operation of the vehicle.

ENUNCIATOR PANEL LIGHTING

Enunciator panels/systems and warning/caution/advisory lights/indicators (there are as many names for them as there are configurations), have only one thing in common: astronauts, pilots, and crew members complain about them. "They are too bright." "They are too dim." "The legends are in the wrong place." "There are too many of them." "There are not enough of them." "They are located where you can't see them." "They take up too much prime space." "They are categorized wrong," etc. The only thing that is consistent is the inconsistent design, location, and human engineering. The solution for correctly presenting warning/caution lights in a crew station is controversial and, in the present state of the art, not entirely satisfactory. Warning/caution lights, as such, have two specific requirements for their illumination characteristics. First, in daylight operations the warning/caution indicators must be able to outshine the sun; the second requirement is that at nighttime the intensity of the light must be such that actuation of the indicator warns the pilot that something is amiss, but does not necessarily scare the hell out of him. To date, the warning/caution indicator on a crew station instrument panel that can be clearly discernible under all conditions of daylight lighting has not been invented. Current warning/caution lights have not attained their effectiveness because of their illumination capacity and their effectiveness often depends on the air vehicle's attitude with respect to the sun.

I realize that I have been quite critical and at this point offer no concrete solution to this problem. It would seem that inherent improvement in warning indication systems using other than warning lights per se should be investigated more thoroughly; and, yet, although I have personally crusaded for improvement in these systems for the last ten years, along with others, there has been no significant improvement in this problem. Since the eye is quick to detect motion, a moving needle or flag device would seem more appropriate as a master indicator than a small lamp illuminating, which in spite of valiant efforts on the part of crew station lighting engineers cannot yet match the illumination capabilities of the sun.

This same problem in contrast offers an interesting aspect to the use of warning/caution lights during night operations. Although it is conceded that the overall illumination of the warning indicator should be reduced for night operation, there is still a tendency to over-illuminate on the premise that it is imperative the crew member not overlook the warning signals. But, illumination of a warning/caution indicator at night usually portends trouble for the crew member. When the message has been delivered and he is aware of some specific trouble, an extra bright warning/caution light staring at him adds no solace or comfort. As one test pilot aptly stated, "Bad news should be broken to a person gently."

As one views the total chaos that exists in the warning/caution light systems presently installed in air vehicles, the most obvious fact that stands out is the total lack of standardization. It is doubtful that any two aircraft, whether they be private, commercial, military, or transport, including space vehicles, use the same warning/caution indicating system. Contrast this with the fact that no system on an air vehicle should be standardized more

than this particular one, and you become aware of the safety factor involved.

SPECIAL DISPLAYS

In most modern aerospace vehicles there is now one or more light-emitting displays such as CRTs, TV screens, and head-up displays, that play a very important role in the overall illumination scheme in the crew station. The quantity of light emitted by these devices can be quite high, especially when all other instruments and control panels are set at a low intensity. Thus, control of the intensity of these devices without impairing the contrast of the display presented is an absolute necessity. The location, the color, the size, and the intensity control of these special displays must be given careful attention in the overall configuration of the crew station if a satisfactory illuminated crew station is to be obtained.

CONCLUSION

In conclusion, I have endeavored to express the history and present state of the art which bares the inadequacies and faults of today's crew station lighting systems and have offered some solutions to correct these conditions. I have not dwelled upon the accomplishments that have been made in the field of crew station illumination for aerospace vehicles, and there have been many. *The technology to do an outstanding job is available. The desire among all lighting engineers I have ever met is enthusiastic.* What is still required is to have program managers in both the procuring and manufacturing activities be concerned enough and be knowledgeable of the flight crew member's requirements that they will insist this technology be utilized. Remember the next time you are flying cross-country in your nice comfortable seat in an airliner that your own life may be in danger because of the conditions the crew members who are responsible for your flight are working under. I do not point out the necessarily costly economic impact of tragedies caused by these unsafe conditions, but merely give you food for thought that your own safety may be involved.

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DISCUSSION ABSTRACT

• *Mr. Schmickley, McDonnell-Douglas Corporation:* In lighting and instruments we have been designing military specifications, but not necessarily to pilot performance requirements. We can define lighting in terms of physical measurements such as voltages or luminance, but the pilot's lighting requirements have not been defined. Somehow we need to define performance requirements--perception, interpretation, and readability. I do not know what measurement should be used for readability, but we need one. To comment on CDR Hammack's question about the correlation between preference and performance, consider the method presently used to determine whether the lighting system is acceptable. Somebody just sits in a cockpit lighting mockup for five minutes, turns the lights down, and makes a judgment about whether the lighting is good or bad without actually going through a mission in it. I do not believe this is the right way to evaluate crew station lighting. My question, Mr. Godfrey, is what method can we use to evaluate lighting other than a customer lighting mockup?

• *Mr. Godfrey, North American Rockwell:* There are a number of ways to evaluate lighting. I do not know whether they are economically feasible or acceptable from a human factors standpoint. But I do know that the labor of a large company to build a crew station cannot be evaluated in eight hours by up to 60 people, at least half of whom have never seen that cockpit before, who spend five minutes in there with the lights turned on. You end up with a bunch of questionnaires and a bunch of chits, all of which are different, and the end result is a bunch of compromises. Now, we all know that there is a better way to evaluate cockpit lighting than that. I think this question would warrant a detailed study by people more knowledgeable in the subject than I am.

• *Mr. McMains, Jay-El Products, Inc.:* I recommend that JANAIR fund and conduct a program to determine the needs of the pilot and crew. The questionnaire should be designed to determine (a) what pilots prefer

in lighting color, (b) how lighting affects performance in various aircraft, (c) what pilots are "living with" and what are the suggested alternatives, (d) what they would prefer eliminated, (e) how they associate safety with lighting, etc. Information should then be condensed and compiled into an up-to-date guideline document for crew stations design. The information should pertain only to lighting.

• *Mr. Waruszewski, USAF Aeronautical Systems Division:* I feel that we have solved the hard instrument lighting problems in present-day cockpits. But what about the CRT problem? With CRTs, you have an area of light shining at you. What has been done to determine the proper light level for these displays? In the TV mode, do you still want seven shades of gray for identification purposes? Tests run during takeoff and landing show that pilots turn the lights way down low--and in terrain following we have found that they are turning them down to near .07 foot lamberts. When you turn a CRT down this low, you can barely see any shades of gray.

• *Mr. Godfrey, North American Rockwell:* The illumination that is emitted by a CRT does not come under the responsibility of the illumination engineer. That is not right, but that is what has happened. The largest light-emitting device in the cockpit--maybe even two of them--which can louse up the whole lighting system, is not the responsibility of the illumination engineer. So, although I do not know the answer to your question, I think it is an important one.

• *Mr. Waruszewski, USAF Aeronautical Systems Division:* This is what I was proposing--that something should be done in this area.

• *Mr. Godfrey, North American Rockwell:* I am going to make a note of this question and bring it up in my own FAE committee, because that is the type of thing we do.

• *LCOL Ravenelle, USAF Aerospace Medical Research Laboratory:* I am a little dismayed that you forgot to discuss the ultimate solution. Every fighter pilot knows that it is simply masking tape. You start with a big roll--experience tells you which lights to cover before you even strap in--and then you have to be ready for the surprises with small pieces. You put those along the side of the canopy and you are ready to grab.

• *Mr. Godfrey, North American Rockwell:* Another method, as you know, is to pull off the lens and break the lamp. You have to get rid of that lamp because if it is raining like the devil, and you have a stupid light there, you will not be able to land. Breaking the lamp or covering it with masking tape is a beautiful solution for a multimillion dollar vehicle.

• *Mr. Baumunk, McDonnell-Douglas Corp.:* I agree that the design of cockpit lighting should not start after the instruments have been designed. You have to start by designing the instruments so that their total complement in the cockpit is uniformly readable under daylight conditions, all unnecessary clutter is eliminated, and the individual instruments are designed as simply as possible. Proper instrument design makes the lighting job a lot easier.

I would like to discuss a concept that has been developed over the last two years which I will call the low-intensity readability concept. I believe this is an approach to solving the total cockpit lighting problem. Using the low-intensity concept, all instruments would be designed so that their lighting at pre-defined low light level would provide for uniform readability of the instruments. It can be easily demonstrated that when you do meet a uniform level of readability at low intensity, you then can increase the brightness of all the instruments to their maximum level and still read the instruments very well even though you have a wide disparity of brightness at a higher level. Now, this concept causes a lot of controversy because it is difficult to measure illumination with standard photometric instrumentation at the low levels and, therefore, to specify lighting in terms of foot lamberts or luminance levels. However, this concept has been developed on a past airplane that we built, and I believe rather successfully. So, I would suggest that this committee and your workshop consider this concept.

• *Dr. Jones, McDonnell-Douglas Corporation:* I would like to go a step further than I think you have gone today. You said it is dangerous to design instruments individually because when you try to integrate them, you have problems. When we were involved in the first stages of the Mercury program, we found that many factors interact with crew station visibility--pressure suits, acceleration levels, hypoxic levels, and a whole series of similar things. I would advise you not to stop at the level you described, but try to integrate all factors that could influence man's vision in the system.

• *Mr. Godfrey, North American Rockwell:* I can't argue with that.

• *CAPT Hawkins, KLM Royal Dutch Airlines:* Mr. Godfrey, when you go into your office in the dark and you want to illuminate the office, you operate one switch and your working area is illuminated. In a large transport

aircraft, the pilot has something like 20 controls to operate before he has established the correct illumination of the cockpit. The situation is getting worse with the introduction of gas discharge displays, CRT displays, EL displays, and so on. Each one, it seems, comes up with its own lighting control. Can you in your workshop give some consideration to limitations on the number of controls required to establish a correct cockpit illumination?

• *Mr. Godfrey, North American Rockwell:* This is an important problem and one that can be solved. Unfortunately, many design people are ignorant of the pilot's needs. So they go by the specifications which are so general that it can be hard to interpret their meaning. To achieve better lighting design we need to bring this out and work to correct it.

• *Mr. Friedman, Naval Missile Center:* In line with your discussion of balanced lighting, I submit that part of the problem is caused by the frequent requirement to use existing off-the-shelf hardware. No matter how hard you try, there is no way to achieve balanced lighting when you must use equipment from an inventory that has been built up over many years. That seems to be the crux of many of today's lighting problems. Half of the displays are new and half are old.

• *Mr. Godfrey, North American Rockwell:* I just got through working on an aircraft secured by multi-service that actually ended up having some red and some white controls because they bought off-the-shelf equipment. So your point is well taken. Again we are back to management and economics and the ignorance I just mentioned. The people who make the decisions do not know how detrimental the decision is going to be. Incidentally, have you ever found a program manager who can talk to you about illumination? I have not, and that is the problem.

• *LCOL Boren, USAF Aeronautical Systems Division:* I propose that the military services and industry convene a working group to resolve the issue of red versus white lighting for cockpits--to be supported by research funds if necessary. Compulsory arbitration if you please! All agencies and industry would be *bound* by this decision. It is essential that we eliminate this unnecessary roadblock--a roadblock so readily identifiable and one within the realm of correction by the participants of this conference.

WORKSHOP PROCEEDINGS

CHAIRMAN: MR. GEORGE W. GODFREY, NORTH AMERICAN ROCKWELL

WORKSHOP DISCUSSANTS

MR. MYRON L. BAKER, Coastal Dynamics Corp.
MR. NICK H. BENSUSSEN, Photo Research Division, Kollmorgen Corp.
MAJ JOHN K. CROSLEY, Army Aeromedical Research Laboratory
MR. ROBERT E. DeMUTH, Grimes Manufacturing Company
LTC JACK D. HILL, Army Aviation Test Board
MR. CHARLES L. MARTIN, JR., Army Aviation Test Board
MR. MARSHALL J. McDONALD, Naval Ammunition Depot
MR. BILL D. McMAINS, Jay-El Products, Inc.
MR. LEWIS W. MYERS, Coastal Dynamics Corp.
MR. JOSEPH OZIMEK, Naval Air Systems Command
MR. DENNIS L. SCHMICKLEY, McDonnell-Douglas Corp.

ABSTRACTS OF WORKSHOP PAPERS

LED MEASUREMENTS

N. H. Bensussen
Photo Research Division

This paper presents an overview of photometric measurement principles and describes the major problems associated with the photometric measurement of light emitting diodes (LEDs). The paper also describes an instrument that has been built to measure LED integrated illumination by photometric methods and a second instrument being built for LED measurement by both photometric and radiometric methods.

ELECTROLUMINESCENCE: STATE OF THE ART

Robert E. DeMuth
Grimes Manufacturing Company

This paper reviews the state of the art of electroluminescent panels. It describes the construction of electroluminescent lamps and discusses the physical parameters that are important in the design of an electroluminescent panel. A series of graphs displays the photometric characteristics of existing lamps and panels. Both color and intensity characteristics are reviewed.

WORKSHOP HIGHLIGHTS

INTEGRATING MEASURES OF ILLUMINATION AND LIGHTING

• *Mr. Godfrey, North American Rockwell:* Although the light emitted by individual displays and indicators can be accurately measured, we still have no way to integrate the individual measures into a composite index to assess the adequacy of the *total* crew station lighting. One reason why such an integrated measure has not been developed is that we do not know enough about the relationship between the physical measures of light and the pilot perception of information. A meaningful method for integrating individual light measures is one of the most important needs of the illumination engineer. This problem is particularly severe in modern cockpits because of the many types of light sources present.

VISUAL PERFORMANCE REQUIREMENTS

• *Mr. Schmickley, McDonnell-Douglas Corporation:* Illumination and lighting in the crew station are, of course, designed to meet the visual performance requirements of the crew. However, there is no good working definition of visual performance. There have been studies in which illumination was related to visual performance by means of subjective judgments, but the results of these studies have not been sufficiently quantified to develop general lighting specifications.

• *Mr. Godfrey, North American Rockwell:* I have been in the lighting business for more than 20 years and I still do not know what the pilot's vision requirements are or exactly how lighting affects the pilot's performance. There is great need for a research program to define pilots' visual performance requirements in sufficient detail to permit the designer to translate these requirements into lighting requirements. If this were done, I feel the lighting technology is available to build a system that will fulfill all of the lighting requirements.

• *MAJ Crosley, Army Aeromedical Research Laboratory:* Perhaps the most important recommendation we could make is for a large-scale investigation to assess visual performance requirements for a variety of aircraft and missions. A joint services organization such as JANAIR might be the logical agency to sponsor this type of research effort.

REFLECTION IN THE COCKPIT

• *LTC Hill, Army Aviation Test Board:* The task of developing an adequately illuminated crew station goes beyond the light-emitting sources themselves. The airframe must also be considered as a part of the lighting system since light can be reflected from it. Reflection has been recognized as a problem for many years, but the problem is still with us. For instance, reflected light constitutes a severe problem in many current helicopters, particularly when you are trying to make a night landing. The crew station in these vehicles is a blur of reflected light from painted surfaces, the windscreen, and the instrument panel covers. The efforts of the lighting engineer and the airframe designer must be more closely coordinated if the reflection problem is to be solved.

• *Mr. Godfrey, North American Rockwell:* I agree the lighting engineer and the airframe designer should work more closely. A related problem is that airframe specifications never take into account the airframe's impact on the crew station lighting system.

• *MAJ Crosley, Army Aeromedical Research Laboratory:* Our studies of the reflection problem show that about 90 percent of the reflected light could be eliminated with the judicious application of paint, slight redesign of the instrument panel cover, and a few other minor modifications. So the problem is clearly the result of inadequate design by the manufacturer. The reflection problem is recognized in our specifications, but the design requirements are stated in such general terms that the manufacturer can interpret them any way he chooses.

THE DUAL LIGHTING ISSUE

• *MAJ Crosley, Army Aeromedical Research Laboratory:* Another problem is the color of cockpit lighting. I do not wish to discuss the red versus white lighting issue; we cannot possibly resolve that issue here. We have had special meetings lasting days, and have not been able to resolve it. The issue I want to address is that of dual lighting--that is, a system in which a pilot can select either red or white lighting depending upon which color best suits his needs at a particular time. But is it economically

feasible to even consider dual lighting in the cockpit?

• *Mr. Godfrey, North American Rockwell:* Some airlines are presently using dual lighting systems, so they obviously consider them to be economically feasible. However, there are probably other lighting methods that are more economical than the technique of equipping each instrument with two differently colored lamps. Fiber optics may be an effective way to provide dual lighting. You could develop a system where fiber optics cables would carry light from a single, centralized light source to each display and indicator. Fiber optic lighting is being used effectively to light automobile display panels, and will probably become operational in automobiles within the next year or so.

• *MAJ Crosley, Army Aeromedical Research Laboratory:* The beauty of this fiber optic system is that the color of cockpit light could be changed by merely turning off one lamp and turning on another. Providing a single backup lamp for each color would give you the needed system reliability.

LIGHTING MOCKUP REVIEW

• *Mr. Schmickley, McDonnell-Douglas Corporation:* There is no doubt that a lighting mockup can provide a great deal of useful information. However, there are two important problems with the usual mockup reviews. First, the mockup review is not conducted until a few weeks before you are scheduled to start building the first prototype model for the aircraft. This means that there is precious little time to find solutions for the problems discovered during the mockup review. Another problem concerns the evaluation procedure itself. The evaluators typically walk from a brightly lighted room into a dark room, look for five minutes at the cockpit with all panels at maximum brightness, and judge whether the lighting is adequate or inadequate. Such a procedure does not provide a valid assessment of the operational suitability of the crew system lighting. So, I feel that mockup reviews should be conducted earlier in the developmental cycle and that judges should be required to fly a simulated mission in the cockpit before they assess the adequacy of the crew station lighting.

• *Mr. Ozimek, Naval Air Systems Command:* I think lighting mockup reviews are conducted too early. The Navy generally requires a lighting mockup review 120 days after the contract is awarded. Many times the contractor has proposed instruments for the new aircraft that have not yet been developed and cannot be developed within this 120-day period. So when the lighting mockup review is conducted, as many as 50 percent of the instruments may be absent, and the customer has the option of either approving the lighting system with much of the relevant equipment missing or being responsible for a delay in the schedule.

• *Mr. Godfrey, North American Rockwell:* I do not believe that simply delaying the mockup review will solve the problem, because you have no assurance that the contractor will use the additional time properly. That is, if you delayed the review for another couple of months, the contractor still might not have all the equipment in the mockup. It might be better to have an initial review 120 days after the contract is awarded, and a final review 120 days later.

• *Mr. Ozimek, Naval Air Systems Command:* We plan to rewrite our lighting mockup review specifications to cover this problem. If the mockup review must take place before certain displays are available, then the panel space to be occupied by a missing display must be illuminated in the exact manner of the forthcoming display. If the customer buys the lighting system, the manufacturer will then be held accountable for building the display to meet the lighting specifications agreed upon.

• *Mr. Myers, Coastal Dynamics Corporation:* I think the individuals who evaluate the lighting mockup should be required to spend at least two hours in the mockup before making a firm judgment about the adequacy of the lighting system. It takes at least this much time to become dark-adapted and to gain a reasonable understanding of the display and indicator functions.

• *MAJ Crosley, Army Aeromedical Research Laboratory:* I recognize that it is not feasible to develop a dynamic mockup within 120 days after the contract is awarded. However, the lighting should be evaluated under simulated or actual operational conditions at some point during the developmental cycle. I see no way to make a valid assessment of crew station lighting without trying to perform some of the same tasks that will be required of the pilot in the field.

EXTERNAL LIGHT SOURCES

• *MAJ Crosley, Army Aeromedical Research Laboratory:* Stray light from external light sources--such as anti-collision lights--should be considered in designing and evaluating cockpit lighting. A well designed cockpit lighting system can be seriously degraded by light coming from the outside of the airplane.

• *Mr. Godfrey, North American Rockwell:* I believe that the specifications and standards dealing with external lighting are far too general. I also believe that too little

attention is paid to external lighting during the lighting reviews conducted by the customer. The external lighting review for one of our newest and most expensive airplanes was conducted in a hanger where the reviewers spent about 30 minutes walking around the outside of the aircraft before signing off on the system. No consideration whatever was given to the possible interaction between the external lighting system and the cockpit lighting system.

• *Mr. Schmickley, McDonnell-Douglas Corporation:* The problem you described is not limited to the external lights of the pilot's own aircraft. When two or more aircraft are flying in formation the external lights of another aircraft may adversely affect a pilot's performance. A pilot cannot merely avoid looking at the external lights of the other aircraft with which he is flying because the lights are about the only cue he has about the position of the other aircraft.

INTEGRATING GFE EQUIPMENT

• *Mr. Godfrey, North American Rockwell:* The policy of using GFE equipment whenever possible has many economic and logistics advantages, but the contractual obligation to use GFE equipment in new aircraft makes it difficult if not impossible to achieve a fully integrated lighting system. In many cases, a piece of GFE equipment was designed to 1950 requirements and specifications, and such an instrument is usually so incompatible with modern displays and indicators that an integrated lighting system is simply not possible. I feel we must stop trying to mix 1950 equipment with 1980 equipment.

• *Mr. Ozimek, Naval Air Systems Command:* You do not think for one minute that anyone would put a 1950 instrument into a 1980 aircraft without considering whether the instrument will do the job.

• *Mr. Godfrey, North American Rockwell:* I am sure that someone considers the pros and cons of using GFE equipment in preparing the RFP. But the fact remains that it is often impossible to achieve an integrated lighting system when GFE equipment must be used. I do not think any lighting engineer will disagree with that statement.

• *MAJ Crosley, Army Aeromedical Research Laboratory:* The primary cause of this problem is that the lighting concept used for the GFE equipment is often entirely different from lighting concepts for modern displays and indicators. The older instruments typically used post-lighting whereas the new instruments use integrated lighting, electroilluminescence, or something else.

• *Mr. McDonald, Naval Ammunition Depot:* That is true. In most cases, it is not possible to achieve compatibility by changing the lighting of the GFE equipment; you would have to change the basic design concept.

INADEQUATE SPECIFICATIONS AND STANDARDS

• *Mr. Martin, Army Aviation Test Board:* A fundamental cause of many of the problems we have identified during this workshop is that existing specifications and standards are inadequate.

• *Mr. McDonald, Naval Ammunition Depot:* I agree. Although each component in a crew station must meet the requirements set forth in a specification or standard, there are no specifications and standards that apply to the *total* system.

• *Mr. Godfrey, North American Rockwell:* Existing specifications and standards are based too much on committee action and too little on empirical research, and I think this should be changed.

• *Mr. Schmickley, McDonnell-Douglas Corporation:* The specifications and design handbooks for crew stations are fragmented and often contradictory. For example, we have different specification documents for panel designs, for individual instrument designs, for instrument markings, and for interior lighting. The design guidelines contained in one document may be incompatible with or contradictory to the design guidelines contained in one or more of the other documents. I also think the documents are far too general. Two instrument manufacturers can use the same specifications and come up with entirely different instruments.

• *Mr. Ozimek, Naval Air Systems Command:* I agree that most of our specifications and standards have been established by committee and have not been based upon empirical research as they should be. I also agree that there may be inconsistencies among the various specification documents that contractors must use. However, the organization that I work for constantly reviews and updates standards and specifications. We send preliminary copies of specification documents to a large number of military and commercial organizations for their review and comments. Contractors constantly complain about specifications and standards, but they seldom take the trouble to comment on the preliminary documents that we send them. I can assure you that the specifications and standards would be changed if contractors would inform us of any inconsistencies and conflicts they find that apply to crew station design. In the meantime we will base specifications and standards on the best available experimental data. Incidentally, those responsible

for writing specifications and standards are now giving much more consideration to lighting integration than in the past.

WARNING, CAUTION, AND ADVISORY INDICATORS

• *Mr. Godfrey, North American Rockwell:* The services and manufacturers need to agree on some concept of warning, caution, and advisory indicators. This entire field is in a state of chaos. One particularly severe problem concerns the onset of a bright red warning light during a critical flight maneuver when the pilot most needs his dark adaptation. Conversely, the same warning light that causes such a problem at night cannot be seen at all when the cockpit is flooded with bright sunlight. I believe it would be a good idea if JANAIR were to fund a study, covering all the service requirements, to establish the relative merits of various concepts for warning, caution, and advisory indicators, such as voice warning, bells, buzzers, motion indicators, and warning lights.

• *Mr. Martin, Army Aviation Test Board:* A great deal is already known about the relative merits of the systems, but due to ancestor worship of red lights, bells, and horns, we cannot get them out of the cockpit.

• *Mr. Schmickley, McDonnell-Douglas Corporation:* But aren't the requirements different for different aircraft?

• *Mr. Godfrey, North American Rockwell:* The specific requirements may differ among aircraft types, but I think there is probably one single concept that would be best for all aircraft, and that an unbiased agency such as JANAIR could conduct an evaluation to identify this concept. Then a specification should be written that applies to all services and aircraft, including commercial aircraft. Manufacturers would have to tailor the caution, warning, and advisory system to each aircraft, but they should not be permitted to deviate from the basic concept.

MODIFICATIONS AND DETERIORATION

• *Mr. Godfrey, North American Rockwell:* We all know that the crew station undergoes frequent modification throughout the life of an aircraft. Many of these modifications--especially those involving displays--can seriously degrade crew station lighting. Yet there is no formal procedure for reevaluating crew station lighting after modifications have been made. I believe that many serious lighting problems would be eliminated if lighting specialists were routinely brought in to reassess the lighting system after each modification to the crew station. Lighting specialists should also be used to assess the effect of display deterioration. For example, an edge-lit panel may look perfectly good when it is new, but after a few months of use it can become scratched and marred by maintenance technicians, covered with dust or grease, or adversely affected by exposure to direct sunlight. If brightness measurements were made on this display back in the laboratory, it would not come close to meeting the specifications. The system the pilot is flying may be seriously degraded after a few months of operational use, but we never know this because we never reevaluate our operational systems.

• *MAJ Crosley, Army Aeromedical Research Laboratory:* I agree that we should periodically evaluate the lighting in operational systems, but it is difficult to measure lighting in an operational cockpit, primarily because our measuring equipment was not designed for use in the cockpit. For example, when you place a photometer in the pilot's head position, there is usually a firewall directly behind the pilot's seat that prevents you from looking through the photometer. To complicate matters, it is difficult to get a constant voltage source into the cockpit. Until we build better measuring equipment, we cannot even determine whether the system that comes right off the assembly line is what was agreed to at the lighting mockup review.

THE MANAGEMENT PROBLEM

• *Mr. McMains, Jay-El Products, Inc.:* We have all listed a number of complaints during this workshop. The function of this group should be to define what is *causing* these problems. Offhand I would say that the technology is available to solve nearly any of the lighting problems that have been mentioned at this workshop. So why do these problems exist? The acquisition procedure seems reasonable and appears to be the same as for most systems. A company designs equipment to a set of specifications, they build a lighting mockup, the mockup is reviewed and modified, and eventually a production item is developed. The procedure is systematic, and qualified people seem to be involved, but there are still problems with the finished product. I recognize that specifications and standards are not perfect and that the lighting mockup review procedure could be improved, but I do not think these are the only causes of problems.

• *MAJ Crosley, Army Aeromedical Research Laboratory:* Another important factor is that only a small proportion of the human factors inputs ever get into the system. Human factors recommendations are repeatedly ignored by both government and industry.

• *Mr. Godfrey, North American Rockwell:* The process we use to develop crew stations is inadequate. At the time of crew station design, management is occupied with more

pressing matters--getting money, meeting schedules, and so on. The result is that inadequate attention is paid to lighting considerations. As John said, the human factors engineer and the lighting engineer do not get the manager's ear soon enough and often enough.

Mr. McMains, Jay-El Products, Inc.: Are you saying that management, or the lack of it, is the basic cause of the problem?

• *Mr. Godfrey, North American Rockwell:* As you said, the technology is available to build a very good lighting system. So I feel that one of the most important causes for lighting problems is that management does not attach a high enough priority to lighting systems.

• *Mr. Martin, Army Aviation Test Board:* I think if we are to get the type of program we want, we must relate our recommendations to safety. If you can show that a design problem constitutes a safety hazard, you can get management's ear and you can get action. I doubt that the safety organizations can provide us with the information we need because accidents are seldom attributed to inadequate design. Accidents of this type are typically attributed to human error, and the pilot is usually not around to argue the point.

• *Editor's Note:* Major John Crosley (Army Aeromedical Research Laboratory) and Mr. Dennis Schmickley (McDonnell-Douglas) were given responsibility for drafting a preliminary set of recommendations based upon the workshop discussion. The following recommendations were presented for review by the remaining workshop members.

• *MAJ Crosley, Army Aeromedical Research Laboratory:* Adequate aircraft cockpit lighting is essential for the safe operation and successful accomplishment of military or commercial missions. An adequate lighting system must enable pilots to read their displays in conditions varying from direct sunlight to total darkness. This committee recognizes that severe deficiencies exist with present cockpit lighting. The major deficiencies defined by this committee include the following:

- There is no adequate definition of pilot's lighting requirements and the effect of lighting on pilot's performance.
- There is inadequate coordination and cooperation among the procurement agencies in developing design standards and specifications and in developing standardized procurement procedures.
- There is inadequate communications between design personnel and management in both government and industry.
- The visual subsystem is not recognized as a major component of the manned system.
- There is insufficient standardization of light measurement procedures.
- Pilot performance criteria have not been adequately defined.
- Test and evaluation procedures are inadequate, especially the cockpit lighting mockup review.
- The responsibility for solving lighting problems and issues has not been delineated within either government or industry.

This committee recommends that the deficiencies stated above can best be resolved by a joint agency composed of representatives from at least the following agencies and organizations: Army, Navy, Air Force, NASA, FAA, aircraft manufacturers, and display manufacturers. The representatives should possess sufficient authority within their respective organizations to ensure positive action.

When our recommendations are presented to the general forum, we should spell out some of the specific problems in more detail. For example, we should mention such problems as: the dual red-white lighting issue, stray lights, glare, the warning, caution, and advisory indicator problems, and so on.

• *Mr. Godfrey, North American Rockwell:* Whatever our workshop may have lacked in numbers, we made up for in enthusiasm. These people were deeply concerned about the problems of illumination and lighting in crew system design. Like the other workshops, we had our initial frustrations and complaints. We tried listing these problems on the blackboard and soon ran out of blackboard. Then we found that we were listing problems and not their causes. So, acting somewhat like a sheepherder, I tried to move the discussion in a direction that would allow us to present a few definitive conclusions to this conference. I was able to pin the conclusions down to just three main points. If you could help us accomplish three things, I think we could solve a tremendous number of these problems.

Underlying all our problems is the fact that we do not know what the aircrew member needs. We do not know. For instance, we talked about the one-inch engine indicator that the pilot sees with the same pair of calibrated eyeballs that he uses to see the big five-inch ADI. Both instruments comply with the same lighting specifications, and I can go into the darkroom and prove it; but I will guarantee that the pilot will tell you they do not. We talked about CRTs which are being put into cockpits almost routinely. Yet I have not found anyone who can tell me how those CRTs affect the ambient illumination in a crew station or a man's night vision. I will tell you what the presence of a CRT really does: it knocks out the whole crew station illumination system. How can you tell me that a pilot needs red lighting when you put a purple CRT in front of him? We feel we have the technology to solve most of our illumination and lighting problems if we can find out what we really need to do. We do not know how many pilots have been killed because they did not see what they should have seen. They could not come back and tell us.

So, first, what color do we need to put in the cockpit? We do not need four colors to illuminate displays so that a pilot can see what he is doing. I have been in this business a lot longer than I am going to say, and I know you can find scientific data to prove the superiority of any color you choose. We need someone up top to get together with the Army, Navy, Air Force, NASA, and the commercial airlines and decide what color or two colors we should put in a cockpit. We can illuminate a cockpit with red light, white light, or both, if you tell us that is what you want. The Navy is spending billions of dollars buying aircraft in which the illumination is partly red and partly white. The Air Force is doing the same thing. That is absolutely inconceivable to me, when all we really need to do is to find out what color is really needed. I will guarantee you that industry can give it to you. But we do not know.

That decision can almost be made arbitrarily. But a decision that cannot be made arbitrarily is the question of the crew member's requirements. How can you tell me that an indicator or a CRT must have a certain illumination level when you cannot tell me what the pilot needs to see? And you can't tell me what he needs to see.

A gentleman commented in this room the other day that we often talk to pilots about their needs and end up learning their preferences but not what affects their performance. I would like to know what impairs their performance. This is going to take some time, money, cooperation, and open-minded men. But we are now literally working with a safety factory in this country. Airports are complex and busy, cockpits are almost incomprehensibly complicated, and not to know what the operators need is almost beyond my understanding. Yet we do not know.

We procure our vehicles incorrectly. I do not really care who you are or how you are procuring them. We are doing it wrong. We call for a lighting mockup within 120 days after signing the contract. That may be beautiful contract language, but in that short time the lighting mockup in no way represents what you are going to get two years later. Therefore, we have been spending money for nothing.

Warning systems: if there ever was a safety-of-flight item in today's aircraft, that is it. I do not know what we need, but I know that many of the warning systems we have now are inadequate. Do we need a young girl whispering in the pilot's ear, "You have a fire in number three engine?" Again, we do not know what the pilot really needs.

I speak now to the management of this conference. If you can define the color or colors of illumination for a cockpit, we can build it for you. We will participate in any manner that you suggest to help the crew get the illumination they require.

Crew stations are all designed for daylight operations. Then they add the lights to them. That is unfortunate, because it leads to such problems as reflections on the canopy, confusions about whether a light is a warning, caution, advisory, or mode light, and problems of turning off or dimming a warning light. You can solve any of these problems

if somebody will tell you what you really need to do.

So, in summation, tell us what color is needed. Tell us what illumination level is required. And tell us what warning indicators a crew member needs.

LIFE SUPPORT SYSTEMS INFLUENCE ON CREW STATION CONFIGURATION

SECTION VIII

AN OVERVIEW OF LIFE SUPPORT AND THE IMPACT ON CREW SYSTEMS DESIGN

MR. E. R. ATKINS
VOUGHT AERONAUTICS COMPANY

Abstract: *This paper presents an overview of life support as applied to air vehicles, spacecraft, hybrid craft, hydrospace craft, and surface craft. The primary emphasis is on air vehicles. Both military and commercial aircraft are considered. This overview also includes a comprehensive definition of life support and a detailed description of its elements. The impact of life support systems on crew station design is discussed and the state of the art in all life support categories is reviewed. Observations are made regarding the future direction of life support, and some suggestions are offered regarding accomplishments of those goals.*

LIFE SUPPORT DEFINITION

So that we all will be working from the same basic concept, let me define *life support* as the majority of government and industry personnel understand it. Life support consists of the hardware, techniques, and training required to ensure the efficiency and safety of crew members and the safety and comfort of passengers during normal operations, operational emergencies, or catastrophic emergencies requiring abandonment of the vehicle and safe recovery of the crew and passengers afterwards.

Life support is generally divided into three basic categories: (1) vehicle environment, (2) escape, and (3) survival and rescue. I will discuss the significant systems and equipment involved in each category, starting with the military application.

AIRCRAFT ENVIRONMENT

Aircraft environment or crew support, as it is also known, provides normal and emergency support for passengers and crew from the point of ingress at initiation of the flight through egress at completion of the flight. Some of the elements of aircraft environment are:

- Environmental control (heat, ventilation, and air conditioning)
- Atmospheric control (oxygen and pressurization)
- Sustenance and relief (food, drink, and relief)
- Seating and restraint
- Personal equipment (flight suit, boots, etc)
- Protective equipment (helmet, G-suit, armor, etc)
- Survival equipment (survival vest, survival kit, emergency oxygen, etc.)
- Fire protection (clothing, upholstery, etc.)
- Fire prevention (crash resistant fuel systems)
- Impact protection (delethalization of crew station and passenger compartment, crash resistant structure, crash resistant seating and restraint, etc.).

The multicrew and transport or utility type aircraft includes many of the above functions and also equipment such as:

- Rest facilities

- Troop accommodations
- Galley
- Restroom
- Flotation gear.

ESCAPE AND DESCENT

Escape and descent covers all functions and equipment relating to emergency departure from the air vehicle, both on the surface and in flight and includes:

- Emergency ground egress
- Ditching egress
- Manual bailout
- Ejection escape
- Extraction escape
- Crew module escape
- Other assisted escape methods
- Free descent (parachute)
- Controlled descent (AERCAB).

SURVIVAL AND RESCUE

Survival and rescue covers all activities required once crew and passenger have reached the ground or water surface. It involves survival in extreme climates, evasion of enemy, and location and recovery. Included in this category are:

- Flotation devices
- Survival equipment
- Signalling devices
- Communication equipment
- Sustenance
- Fire arms
- Exposure clothing
- Extreme climate clothing
- Evasion equipment

COMMERCIAL AIRCRAFT LIFE SUPPORT

Commercial aircraft are concerned primarily with the inflight environment and emergency ground egress and ditching functions. This category includes:

- Environmental control (heat and air conditioning)
- Atmospheric control (oxygen, pressurization, emergency oxygen)
- Ground egress (slides)
- Ditching (rafts)

In summary, the entire commercial aircraft life support picture is well under control because of the monitoring of many interested groups such as the Airline Pilots Association, FAA, SAE, and the users. Their constant attention has heralded very rapid solutions to the problems posed by the wide-bodied family of aircraft.

OTHER APPLICATIONS OF LIFE SUPPORT SYSTEMS

Although our thrust in this conference is the air vehicle, life support applies to many other types of vehicles:

- Spacecraft - Mercury, Gemini, and Apollo, which pioneered truly integrated crew systems through NASA's farsightedness, show what can be done with the proper attitude.
- Hybrid craft - such as the space shuttle, which combines spacecraft and aircraft operational criteria.
- Hydrospace craft - submersible vehicles which have many problems and solutions akin to aerospace contemporaries.
- Surface craft - high speed trains, ground-effect vehicles, etc., which will benefit from aerospace technology.

LIFE SUPPORT IMPACT

To some degree, life support system hardware has an impact on every air vehicle crew station and passenger compartment design. It influences:

- Ingress and egress
- Comfort and mobility
- Geometry
- Volume and size
- Control location
- Display arrangement
- External vision
- Internal vision.

It has the greatest impact on air vehicles, such as fighters, that require assisted inflight escape, and the least impact on transport and utility vehicles. The ejection seat configures the man as well as the crew station, while the crew module configures the air vehicle. Armor and impact protection configure the structure, while fire prevention configures the systems. The impact is there.

THE STATE OF THE ART

Now that we have defined life support and explored its impact on the crew system, let us proceed to the basic questions this conference poses: Where are we? Where do we seem to be going? Where should we be? How do we get there?

I can tell you where we seem to be going and give a few ideas of where we should be, but after that it gets pretty tough. It is going to take a concerted effort, by such groups as this, to fully define where we should be going and how we can get there.

WHERE ARE WE?

The central character and most influential figure in life support is our aircrewman, or at least his equipment. Today we find our hero wearing, carrying, strapped to, and in general heavily encumbered with all of the equipment that protects him from the hostile environment inflight and on the surface:

- Flight equipment
- Restraint
- Flotation gear
- Anti-G gear
- Oxygen mask
- Armor
- Pressure suit
- Artic clothing
- Exposure clothing.

WHERE DO WE SEEM TO BE GOING?

In the same direction! True, advances are being made; lightweight exposure garments are in the offing; integrated survival gear is under development; work is progressing in every area; but the basic concept of "hang it on the man" remains! Now we even have a part of the weapons delivery system affixed to the pilot's head! However, at least that piece of equipment seems to have sound justification; it improves the weapons system. Most life support equipment on the man was put there as an operational expediency or as an economic concession to the airplane!

Escape. The contemporary scene finds us utilizing all four basic escape modes:

- Manual bailout
- Extraction
- Ejection
- Module.

The direction we are headed toward calls for a reduced use of manual escape and an increased emphasis on extraction. This concept is being considered for such aircraft as the Flying Command Post and Super Tanker. Ejection seats are improving in performance, mobility, and size. Crew modules are improving in performance, but they are still not stressing a key advantage--crew effectiveness through optimum crew stations.

Survival and rescue. Here again the performance improvement looks great, but accomplishing this with concepts like PARD and AERCAB poses a formidable challenge in packaging.

WHERE SHOULD WE BE?

Our overall goal, of course, is to produce the optimum crew system. The shirt-sleeve environment versus the "hang it on the man" environment--the optimum crew system begins or ends with this decision.

HOW DO WE GET THERE?

There are no technical barriers to achieving airline-type crew and passenger environment if assisted escape is not required. The real challenge is presented by the design that does require assisted escape.

The integrated crew module is the obvious answer; however, a great deal more homework is necessary before we will know its total advantages. The non-module escape system is likely to be with us for a long time, and a great deal can be done to unburden the aircrewman. In this situation, this can be accomplished by refusing to compromise the comfort and mobility requirements, by working toward methods for delivering survival equipment to the aircrewman rather than having him carry it, and by working towards ultralightweight, low bulk clothing, and miniature equipment. This will be accomplished only through true creative thinking and a true systems approach.

Some strides are being made in the systems concept. The mission-oriented crew support concept developed by the Navy's Aircrew Equipment Department is a good example, as are the integrated life support system designs now in progress by the USAF Life Support SPO and the survival equipment retrieval and analysis program conducted by the Army's Aeromedical Research Laboratory.

We must also create better tools for doing the job. We must develop and refine analytical and experimental techniques that are pertinent to the product, and even more important, we must establish credibility through practical and believable application and evaluation. To do this, we must be willing to come down from our scientific high

horses and grapple with the realities of operational hardware and people, but without compromise to the basic requirements. We must also know those basics in quantitative as well as qualitative terms and be prepared to defend them effectively on the dollar and performance battlefield.

Probably the best advice I can give to help achieve our goals, regardless of what they are, is to recommend these simple rules:

- Recognize the real world - dollars and vehicle performance are the stuff decisions are made of; engines and airframes are basic--crew systems are not!
- Do our homework - do it better and faster than others; the quality must be there, and it must be timely if we are to be heard.
- Quantify - we must present credible quantitative data and be able to translate into dollars and performance.
- Work as a team - at very best, we in crew systems are small in number and weak in voice. We must pull together.

And of these admonitions, the most important is expressed by the Golden Rule: "He who has the gold makes the rules."

DISCUSSION ABSTRACT

• *Dr. Hitchcock, Naval Air Development Center:* You stated that you doubted that the capsule would become the dominant technique of recovery. I do not doubt your conclusion but I would be interested in knowing what reasons led you to it.

• *Mr. Atkins, Vought Aeronautics Company:* I have to go back to the very basics. Management will not give us the money to do what we want, thereby compromising our position. But, that is really an effect. The real cause is that we have not done our homework. We have not recognized the real world. And, because of this failure, management now has a firmly entrenched attitude that modules are bad. I think that *both* modes should be used in the future. But we have to do the very best job possible to define which modes should go on a particular vehicle. And we have to justify our choices.

• *CDR Hammack, Office of Naval Research:* Your Hawaiian flight suit module sounds good--the shirtsleeve environment. I've heard about this for quite some time but I have always been doubtful that my own management would even let me get in the airplane that way.

• *Mr. Atkins, Vought Aeronautics Company:* John, I think we are right back to the homework problem. Any time we introduce something new to air vehicles--wheels, control surfaces, whatever--we have to convince management of its effectiveness. The crew module is no different. You must get hard numbers to back up your claims, you must think crew systems and somehow persuade management they are needed in your own shop. And when you do generate sufficient management interest, I think you will find that the money required to do the detailed homework needed will be forthcoming.

• *Mr. Macnab, Computing Devices of Canada:* I noticed in my assiduous reading of *The Commerce Business Daily* that one of the places where the gold is starting to flow is in the area of highway safety. And I notice in your categories of applications of life support systems, you did not include the passenger automobile. I would like your comments on that application.

• *Mr. Atkins, Vought Aeronautics Company:* True enough, the automotive vehicle does have a very definite application for our crew systems technology. I do believe that the attention of the government has been secured in this particular area and a lot of activity is going on. And I think that if we in air vehicle crew systems could have made the point as dramatically as the automobile people have apparently done, we would soon obtain the necessary backing to accomplish our job.

• *Mr. Kennedy, USAF Aerospace Medical Research Laboratory:* Dick, I think that although we would all agree that gold is the primary pushing force, we must react as though this is not true. After all, the primary purpose of this conference is not to stick our head in the sand but instead to go after our managers and convince them, however we see fit, that they must use the human factors that we can provide. I would hate to think that just because someone is holding the gold that we cannot influence him to take certain directions in research. After all, we all know of the existence of unsolicited proposals, at least as far as government is concerned.

• *Mr. Atkins, Vought Aeronautics Company:* Your point is well taken, Ken. I do not mean to imply that you should ever lose sight of the total picture. You must have a balanced approach. My point is that if you ever forget what part the money plays, you are dead no matter how good your technical tools are. And going back, it still looks to me like the lack of gold is an effect not a cause. The cause, as I have been emphasizing, is a lack of homework.

• *Mr. Baumunk, McDonnell-Douglas Corporation:* The results of the homework you suggest will fundamentally be used to sell the system, and this type of selling is usually done on the basis of cost effectiveness. Could you outline the specific areas where the homework should be directed? When I think about how you go about deciding whether you escape with a parachute or an ejection seat or a capsule, I want to know how much these systems cost, how much is the crew's life worth, and so on. Can you give an idea of the areas where we do not have the facts and where we should be going?

• *Mr. Atkins, Vought Aeronautics Company:* I think you have pretty well answered your own question. First, I do not believe that the technical questions have been answered, and they certainly have not been related to the dollar. I can think of one very pertinent example, and that is the head-up display where everybody always wants a larger instantaneous field of view. If you put a HUD in an airplane with an ejection seat, there is no practical way to bring the combining glass close enough to give the pilot the field of view he needs. If you remove the requirements for an ejection seat clearance path, you can bring the combining glass as close as you need to provide the required field of view. Hence, you could avoid the cost of developing a HUD with a larger field of view. I am talking about saving a whole bunch of bucks right there--several hundred thousand, I think. And this is true throughout the system. If you take a close look at the problem of the crew system, you would be amazed at how often improved crew systems can be directly related to dollars.

• *MAJ Madson, USAF Aerospace Medical Research Laboratory:* We have done pretty well with our present systems over the past several years, but improved aircraft performance has highlighted problem areas that have slanted us more toward the crew module. Do you feel that it is realistic to say, "shoot for capsular or modular escape systems on all future aircraft of high performance caliber?"

• *Mr. Atkins, Vought Aeronautics Company:* First of all you have to think of this in terms of an optimum crew environment rather than an escape system because modular escape is not efficient in many cases. So when you speak of modules, at least as we know them today, you have immediately armed your enemy to shoot you down. You have to recognize this, but I think my answer to your question would be "yes"--as a goal. If, as a crew systems man, I firmly believe that modules would provide the best environment for the crew, then my lofty goal would be to achieve that objective. However, I must be realistic and recognize that I would get thrown out of the boss' office on my ear if I talked about a module--at least in terms of the way we look at them today--for say a half-million-dollar airplane. But if the necessary work is done on the module environment, it is conceivable that we could completely eliminate what are considered inefficiencies right now.

• *CDR Wherry, Naval Air Development Center:* Dick, I get the feeling that you are sitting on the fence and trying not to displease anybody.

• *Mr. Atkins, Vought Aeronautics Company:* No, not at all, Bob. I have no qualms at all about displeasing people by stating what I believe in. But I am trying to be completely objective. Okay, now go ahead and shoot me down.

• *CDR Wherry, Naval Air Development Center:* I would like to know whether there is really any doubt in your mind that if we approach the life support problem from a crew system standpoint that the module makes sense for the fighter attack community. There is not in my mind, and it would seem to me that this kind of a conference should underscore this need. It is true that if we go into the development of the crew module we would be competing with ourselves for money that would otherwise be dedicated to the independent solutions to problems in life support, escape, displays and controls. But there does not seem to be any doubt that we have to approach this problem with a systematic concern for crew effectiveness.

• *Mr. Atkins, Vought Aeronautics Company:* Bob, I do not disagree with what you say one bit. I believe that would be the correct approach. But again I caution you to be prepared for the enemy. You have to be realistic. Of course, in no way should this realism ever divert you from your end objective.

• *Dr. Roscoe, University of Illinois:* There is one area in aviation that the federal government has recognized as being attached to economic premiums and penalties and that is in certification of area navigation systems. In 1969, the FAA issued Advisory Circular AC90-45 which defines the procedures whereby a manufacturer demonstrates his system's compliance with a predefined error budget. The error budget

includes pilotage error or flight technical error, as the airline folks say. Pilot errors are combined with equipment errors in a geometric fashion, the square root of the sum of the squared errors. This allows you to trade off improvements in pilot performance against a relaxation in the accuracy of the rest of the system. Furthermore, hecause pilot errors tend to be larger than those associated with modern electronic equipment, you might very well trade a 25 percent reduction in pilot error against a 100 percent relaxation in equipment errors, and still come out dead even.

The problem that requires some investigation is the measurement of pilot performance in a way that takes into account not only the variable steering errors in cross track flying or holding altitudes, but also the blunders that the pilots make in operating complex systems. Some experiments that we have been doing reveal that all the action is in the blunder region. The blunders that pilots make in entering waypoint positions and selecting radio frequencies are such that they cause the airplane frequently to fly out of the protected airspace. In other words, to embark upon a course that is not the one they have been cleared for. When that happens, you have a blunder that may very well be catastrophic. So, it is necessary to find some way of measuring the blunder proneness, if you want to call it that, of a system and reducing that blunder proneness to an acceptable level. When you do, you can trade that off against all kinds of savings in the cost of your hardware. So there is money there to be traded.

• *Mr. Atkins, Vought Aeronautics Company:* Stan, that is the kind of needed work that we have been discussing. However, I must point out that the sort of information you have discussed does not fall into the realm of initial aircraft procurement, and therefore cannot be used as a prime example. Because remember, you still have someone with a bag of money that must buy so many airplanes and, unfortunate as it is, the number of airplanes that are ultimately going to crash is not a prime factor in procurement. Certainly not in military aircraft.

• *Dr. Roscoe, University of Illinois:* Perhaps not military, but I would say that in the procurement of civil aircraft, particularly airline aircraft and business jets, I believe that the dollar saving in the initial procurement is quite tangible and would be taken into account. It surely would be taken into account in the selection of the control display unit for an area navigation system.

• *Mr. Atkins, Vought Aeronautics Company:* I completely agree with you Stan.

• *Dr. Jones, McDonnell-Douglas Corporation:* One of the problems with the kind of things we are advocating is that the savings they generate are reflected in life-cycle costs, but not in immediate procurement costs. I think we are barking up the wrong tree by trying to convince the managers who are responsible for procurement dollars. We should be approaching people who are concerned with long-term costs.

• *Mr. Romero, Consultant:* What management is really interested in is weight. I think the capsule could be accepted at any time we engineers walk up to management and say, "the capsule is not going to cost you one ounce of weight more than the ejection seat, and it is not going to delay the schedule." If you can come up with a trade study showing that capsules do not weigh more than ejection seats, management will accept capsules, because the design complications are not that great.

• *Mr. Atkins, Vought Aeronautics Company:* I agree with you in part, but I think that the story is going to have to be told in far more complete terms. Weight is only a part of it. If we are really convinced that the capsule does the job, we must work toward satisfying the total requirements--weight, schedules, dollars.

WORKSHOP PROCEEDINGS

CHAIRMAN: MR. E. R. ATKINS, VOUGHT AERONAUTICS COMPANY

WORKSHOP DISCUSSANTS

MR. MILTON ALEXANDER, USAF Aerospace Medical Research Laboratory
MR. ALFRED C. BARMASSE, American Safety Flight Systems, Inc.
CAPT LAURENCE H. BLACKBURN, Naval Air Development Center
MR. AARON BLOOM, Sierra Engineering Company
MR. GEORGE A. BRONSON, McDonnell-Douglas Corp.
MR. RICHARD L. CARPENTER, NASA Flight Research Center
CDR WILLIAM R. CRAWFORD, Naval Air Test Center
MR. CHARLES P. DAMON, Army Combat Development Command
MR. LOUIS A. GIRARD, JR., Goodyear Aerospace Corp.
MR. JESSE B. HALL, Naval Air Systems Command
MAJ ROBERT L. HILGENDORF, USAF Aerospace Medical Research Laboratory
MR. THOMAS L. KIENHOLZ, Lockheed Aircraft Company
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ABSTRACTS OF WORKSHOP PAPERS

THE EFFECTS OF PERSONAL PROTECTIVE EQUIPMENT UPON THE ARM-REACH CAPABILITY OF USAF PILOTS

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The lack of published arm-reach data on Air Force flight personnel in actual cockpit situations presents manifest difficulties to the cockpit layout specialist. This paper discusses the results of a study to determine the arm-reach capabilities of aircrewmen wearing heavy winter flight clothing, survival equipment, and restraint harnesses.

The study was conducted at Loring AFB, Maine. The sample consisted of 16 male subjects (currently active Air Defense Command pilots). The subjects were selected to approximate closely the various height-weight categories in the ADC flying population. A specially designed apparatus was constructed to measure arm-reach capability. Each subject was measured under four conditions: (1) shirt-sleeved with the inertial reel unlocked, (2) shirt-sleeved with the inertial reel locked, (3) wearing his full assembly of flying gear (hereafter referred to as maximum assembly) including the underarm life preserver and parachute harness with the inertial reel unlocked, and (4) wearing the maximum assembly with the inertial reel locked.

The results of the study indicated that there are significant differences in arm-reach capability of pilots while in the shirt-sleeved and maximum flying assembly conditions throughout most of the spatial envelope.

WORKSHOP HIGHLIGHTS

CREW CAPSULES

• *Mr. Stanley, Stanley Aviation Corporation:* The first capsule I know of was on the X2, designed in 1947 and first flown in the early 1950s. Since that time there have been perhaps three more in this country, and none that I know of abroad. The first operational capsule was used on the B-58. This capsule weighed about 700 pounds. The most recent capsules, used in such crew systems as Apollo, weigh up to 20 times more. So we have a pretty broad spectrum of size difference.

The capsule was going to solve a lot of high speed escape problems, but it has not really lived up to its promise, largely because of a lack of any real desire on the part of the military to use it. Now the decision was made in the early 1950s, in the Air Force at least, that anything that flew at speeds over 600 knots should have a capsule. But despite that edict, we have built a lot of airplanes that fly at speeds well over 600 knots, which do not have a capsule. This gives us some reason to doubt that the original edict was on firm ground. So we analyzed the capsule--what is it, what do you get out of it, why bother if it is going to be too big and heavy? I would like to state what benefits, real or imaginary, are used to justify capsulation.

The most obvious benefit, of course, is protection against wind blast. It is indisputable that when a man goes out at high enough velocity, he is going to be pretty well shaken up or torn up. But what other benefits can a capsule provide? A special vessel can be considered as an auxiliary supply of pressure to save a man's life in the event of explosive decompression at very high altitude. Also, the capsule has uses for survival after escape which have not been exploited. You can well argue, "what is the point of bailing out over the North Atlantic in the winter, all you are going to do is postpone your death about three or four minutes?" But the capsule, with its inherent flotation and housing, offers an awfully attractive means of saving the man's life after his escape. However, since most of our military operations have been in areas with a mild climate, the main emphasis has been on getting the pilot down safely rather than on his survival after reaching the surface of the earth. So basically, people think the major benefits of capsules are: they provide protection from wind blast and depressurization; they provide greater freedom of movement because pilots can fly in a shirtsleeve environment, and they provide a habitat that could help keep the pilot alive after he has reached the surface of the earth. I would like to qualify the "benefit" concerning depressurization. Since there is no reason to believe that combat damage would be confined to places other than the capsule, I think the argument that the capsule is a valuable safeguard against explosisive decompression is fallacious.

Okay now, what is wrong with capsules? Their weight of eight or ten thousand pounds may not constitute a very serious problem because that weight may have been what that particular chunk of the airplane weighed by itself, or the module could be designed to be close to that weight. But one very real and basic problem that will always be associated with big and heavy capsules is that if people are going to come down in them and land at a non-lethal impact velocity, you will have to have a big parachute or a big retro rocket, or a big something that will sustain the heavy modern capsule and permit ground contact at a survivable velocity. Thus far, I do not believe anyone has seriously thought of putting a capsule down with anything other than a parachute. I think it is axiomatic in parachute technology--the bigger the weight, the bigger the parachute. I think it is equally axiomatic that the bigger the parachute, the longer it takes to fill. Carrying the axiom still further, the longer it takes the parachute to fill, the more time you need from the moment you hit the panic button until you have stabilized or at least reached a survivable impact velocity. Now it has been very fashionable for a great number of years to refer to zero-zero capability, and I think we have enough statistics to know that this capability is needed. To take something that weighs five, six, or seven tons at zero-zero and propel it high enough for a parachute to fill and then slow the capsule's descent to an acceptable rate means that you have added a great amount of weight, a great amount of expense, and a rather fabulous amount of testing costs to the capsule. The price of qualifying a multi-place modular capsule is probably in the general vicinity of 75 to 100 million dollars. We therefore need to determine how we can avoid this rather vicious circle of bigger rockets to push bigger capsules to greater heights, and bigger parachutes to bring them down.

Certainly it seems that the easiest way to get a parachute to open in a hurry is to make it smaller. A 28-foot, C-9 canopy-type parachute can pretty reliably get open in well under two seconds. The corresponding time for parachutes large enough to carry the

capsules now in operation is about 12 seconds. Therefore, perhaps there is justification for a hybrid capsule that has a means of escape in the low-speed mode that does not necessarily require blowing the whole capsule off the airplane. It seems to me that such a dual-mode escape system would represent a justifiable compromise. For example, at 400 knots or less, we would use a rather simplified escape system--an ejection seat or an extraction rocket. For speeds above 400 knots the pilot would escape by blowing off the capsule. To do this we would use a crossover sensor which would automatically put the pilot in the low-speed mode when he got below a crossover speed. Above the crossover speed, the entire capsule would go off. And if, for bad weather situations or other reasons, the pilot wanted to use the module for habitation even at the lower speed, we would provide an override switch that would permit him to blow the capsule off.

A peripheral issue here is whether the crew habitation feature of the module is actually necessary. Recently it has come to my attention that many people believe it is not. If this is so, then perhaps we could get by with a capsule with a drogue chute to bring it down, say from 80,000 to 30,000 feet, after which the pilot could blow out with his ordinary escape system.

Decisions about whether habitation is necessary exceed my knowledge and authority. All I am trying to suggest is that there is real justification for taking another look at capsule technology and getting away from the dichotomized view that escape systems must be all capsules or all ejection seats. The technique of cutting away a portion of an airplane which we will call a true modular capsule and of cutting it in such a shape that it will fly reasonably stably does not carry heavy weight penalties. Further, it is not hard to do at all. It is only when you begin to add these enormous parachutes and propulsion rockets that modules begin to get expensive. A great deal of sub-testing and dynamic testing is needed to ensure that all the components work reliably.

• *Mr. Atkins, Vought Aeronautics Company:* As I understand it, Bob, you propose to combine a conventional escape system with a module escape system in a way that will allow the pilot to descend to a desired altitude and then punch out by the conventional means. It sounds like you are getting rid of a big parachute and a big rocket, but in order to do that you could never use the module in a conventional mode.

• *Mr. Stanley, Stanley Aviation Corporation:* No, I didn't mean exactly that. I am saying that for low speed escape, where probably 90 percent or more of the escapes will occur, the pilot will escape by conventional means. The capsule will remain intact on the airplane to go crashing with it wherever it goes. The capsule will be blown off only under circumstances where you really need it for protection, such as speeds above 400 knots, altitudes above 45,000 feet, or both. Then you might have either of two choices. If the capsule is needed for survival after reaching the earth's surface, then put on a big enough chute to bring it down. If it is not important to have the capsule on the ground, and that is certainly being reviewed now, then merely bring the capsule down to a safe altitude and let the pilot punch out of it with his more conventional escape system.

• *CDR Lassen, Naval Safety Center:* I have a couple of questions. I think one of the main advantages of the capsule that I have heard is the provision for a shirtsleeve environment. With the hybrid concept that you proposed, the pilot would still be encumbered by all the equipment he has to wear now because he would never know which escape mode he was going to use. Thus, he would always have to be prepared for the worst, as he is now.

• *Mr. Stanley, Stanley Aviation Corporation:* I presume you are talking about either full- or partial-pressure suits.

• *CDR Lassen, Naval Safety Center:* No, I am talking about exposure suits, life preservers, survival vests, oxygen masks--all the equipment he needs to survive. When we think of modules, we think of pilots flying around in dungarees and coming down in the module unencumbered. But the hybrid module you describe will not provide this shirtsleeve environment if most of the time pilots will be using ejection seats to escape. They will have to continue to wear the encumbering equipment they are wearing now--and they are miserable now.

• *Mr. Stanley, Stanley Aviation Corporation:* I must confess that when I said shirtsleeve environment, I was thinking largely of the full-pressure or the partial-pressure suit. Obviously, in order to survive in an ejection seat or extraction escape system, you have to have a survival kit.

• *Mr. Bloom, Sierra Engineering Company:* It would appear that if you reduced the limits of your ejection environment by using a hybrid capsule you could probably save a considerable amount of weight and also save on the hardware you are talking about.

• *CDR Lassen, Naval Safety Center:* Yes, that would be possible but Mr. Stanley did mention a cutoff speed of three or four hundred knots. We need everything we have and more at four hundred knots.

• *Mr. Bloom, Sierra Engineering Company:* Well the crossover velocity of 400 knots struck me as a relatively arbitrary value. You might use a slower crossover velocity. If you could, then the compromises might be justified.

• *CDR Lassen, Naval Safety Center:* Yes, but you must take into account that requirements for a helmet, oxygen mask, and exposure suit have nothing to do with ejection speed. So, I do not see the correlation between ejection speed and the gear the pilot must wear.

• *Mr. Bloom, Sierra Engineering Company:* I must admit I stopped short of all these new developments.

• *Mr. McLaughlin, McDonnell-Douglas Corporation:* I think in evaluating the benefits of a capsule, you also have to consider the mission of the aircraft. If it is a fighter, the man's going to have to wear at least a G suit of some sort. He probably could not avoid wearing a G suit even if he were in a hybridized capsule.

• *Mr. Stanley, Stanley Aviation Corporation:* I do not know what other people mean when they say shirtsleeves. The term is very freely used. Up until today I had assumed that it largely referred to pressure suits, but if the shirtsleeve people are actually wearing dungarees, which I doubt, then they have gone further than I thought.

• *Mr. Atkins, Vought Aeronautics Company:* Bob, I do not think either of you had the benefit of the earlier presentation when the advantages to the aviator of flying in a crew module were stressed. Basically, the goal is to put a man in a K2Z flying suit. Now perhaps you might give or take a little bit--right now they are using hard hats with G suits. I personally believe that ultimately they can be dispensed with. In an ideal shirtsleeves environment the pilot would walk in, and sit in his workplace, take off his jacket and go to work. That is the baseline that we are referring to in most of these questions that have been brought up.

• *Mr. Mancinelli, Naval Air Development Center:* If we are talking about a capsule we are talking about something to be used in the 1980s, not something that will be used tomorrow. This gives us time to sit down and decide why we need a capsule if we do, what the capsule could do for us, what it could not do for us, what kind of compromises we can make, and whether or not we should have a dual escape system for low-level, low-speed escapes. But right now, we are guessing without any data to base our guesses on. Is it better for a man to wear a coverall and fly his airplane or not. I do not know, I think so. If the pilot were not overtired from flying in a heavily encumbered condition, could he perform better, with greater mobility, and eliminate the necessity for a great many ejections? I do not know. But, I do not think we should put the cart before the horse at this point. I think first we must define what a capsule will do for us. And I do not know anybody who has run a study yet, in an operational situation, or even close, that has determined whether if a pilot had been wearing coveralls he would have performed X number of percentage points better than if he were not. And until we do things like that, we are guessing.

• *Speaker Unknown:* I am afraid I can't quite understand the 1985 time table. We have airplanes being designed right now with capsules; we had a meeting in Palm Springs a few months ago in which a very eminent designer by the name of Kelly Johnson was completely negative toward capsules because of the problems we have talked about. It seems to me that capsules are timely in 1972, not in 1985.

• *Mr. Mancinelli, Naval Air Development Center:* We have to start now, but capsules will not be available to us for quite awhile.

• *Speaker Unknown:* We started back in 1950.

• *Mr. Mancinelli, Naval Air Development Center:* Yes, we started a capsule program in 1950 as an escape system. But right now, I don't think anybody is going to buy a capsule as an escape system only. They are going to buy a capsule that does more than just detach itself from the airplane and bring you down. Somebody is going to have to demonstrate that capsules can contribute to improvement. Areas to be improved include the presentation of displays, the controls, the instrumentation, and the use of available space.

There are other things involved that we really can't do right now. For example, how do we protect the man against nuclear flash, nuclear thermal loads? We try to do it now by loading the man, which again reduces his performance capability. I am not saying we can actually do it but it is possible that these protective systems could be built into the capsule itself. There does not have to be as large a transparency with capsules because we do not have to take off the whole top to extract the escape system. So there is a good possibility we could opaque the smaller transparencies in the time allowed to us to protect the man against nuclear flash or nuclear thermal loads. There is also a better chance of arming the workspace so that the man does not have to be encumbered again with ballistic protection for the combat environment. And there is a

good possibility of coupling the shirtsleeve environment with on-board oxygen generating systems now being developed. The systems can overproduce for a period of time so that you might be able to maintain a certain amount of pressurization even with a leak. I think we should explore these possibilities before we discuss the use of capsules on present-day airframes to find out whether there are advantages in doing so.

• *Mr. McLaughlin, McDonnell-Douglas Corporation:* What you are telling us is that if we are going to sell capsules with the capabilities they show today, which are somewhat less than the operational envelope of an ejection seat or an extraction system, we have to come up with some other convincing reasons for using them. But you have not mentioned the possibility of some technology coming along and giving the capsule essentially the same capability as the seat. Then we would use it even if it cost more, weighed more, and could not do any of the things you just mentioned.

• *Mr. Mancinelli, Naval Air Development Center:* I am not that clairvoyant; I do not know.

• *Mr. McLaughlin, McDonnell-Douglas Corporation:* I suspect that if you could get a guy out at 100 feet altitude or at a 10,000 foot per minute sink rate, and those are obvious tough ones, it would settle whether or not you could do some of the other beneficial functions that you just described.

• *Mr. Mancinelli, Naval Air Development Center:* I think so but I do not think you can be sure at this point. It is still going to be a tradeoff. But you are putting the tradeoff in your favor now by saying you are going to do at least as much as the present escape system has.

• *Mr. McLaughlin, McDonnell-Douglas Corporation:* I did not really mean to put it in my favor. I did not want to tie advancement in escape technology to parachute technology. Perhaps something other than a parachute will be developed to let the capsule down. I just do not want to rule out the opportunity for significant advancement in the escape technology itself.

• *Mr. Mancinelli, Naval Air Development Center:* As far as I know almost every capsule to date has been sold with the implication that it was going to be shirtsleeve and then we nevertheless left enough room in that capsule to include an ejection seat. And all of a sudden it is too heavy and too big. Well, that is because it was not really designed as a capsule. We have always hedged so that in case we had to put a seat in, we were still capable of doing do. I think we have to show that we are competent and confident enough that a capsule is going to be a capsule. But we can't do that without a lot of studying between now and the time we will make the necessary kind of presentation.

• *Mr. Barmasse, American Safety Flight Systems, Inc.:* Dino, let me ask, who is hedging, the customer or the airframe people?

• *Mr. Mancinelli, Naval Air Development Center:* Everybody. The government, the customer, the airframe people, everybody.

• *CDR Lassen, Naval Safety Center:* As Mr. Stanley pointed out, the Air Force decided to put capsules on in the early 1950s. Apparently this decision was based on some kind of study. I think it is very presumptuous for us to say that we need a study to determine the pros and cons of capsules. That is insinuating that the Air Force put a capsule on the B-1 and the F-111 without any sound reasons for doing so. Now the F-111 did not end up with a capsule in the Navy, but I am sure there were people in the Navy who advocated capsules. In any event, I do not think it is right to say we need this kind of study, because I think the Air Force must have done this for the B-1 program.

STANDARDS AND SPECIFICATIONS

• *Mr. Atkins, Vought Aeronautics Company:* Is it the consensus of the group that specifications and standards are still a big problem?

• *Mr. Barmasse, American Safety Flight Systems, Inc.:* About two years ago the Air Force funded a study program to review all of the specifications on life support. What were the results of that study?

• *Mr. Atkins, Vought Aeronautics Company:* We generated a magnificent effort. However, as you well know, nothing happens over night, so I cannot yet tell you what the final results will be. We looked at the entire documentary structure as it existed and then determined what is needed. The result is not what you would have expected. We found that there was a need for a lot more standards and specifications than currently exist. We recommended a complete overhaul and update of the documents to reflect the current state of the art. Some of the recommended documents are in the mill. The aircrew station standardization panel meets three times a year and evaluates all of the basic documents. There is no equivalent activity in life support despite the fact that we have talked about this for a couple of years.

There are several current programs--some Navy funded and some Air Force funded--

in which a contractor is funded to perform the research necessary and to write standards and specifications for a particular airborne weapons system or class of airborne weapons systems. This new approach to aircraft acquisition should have a great impact on the crew station design process in the future.

• *Mr. Solomonides, North American Rockwell:* I think that too many times we use the documentation to hide behind. Rigid standards and specifications preclude innovation by designers and other people who are trying to design a good system. You end up with a mediocre system just so you can protect yourself.

• *Mr. Stanley, Stanley Aviation Corporation:* I do not have any confidence that this issue of specifications and standards can be solved. Can you cite a single case in which the Army, Navy, and Air Force have worked together to design a common specification or standard? That is question number one. Question number two, "how much experience has Chance Vought, Boeing, or Goodyear had in the actual design of escape systems?" I see the word "design" on everyone's name tag, but I don't think any of those three companies have been involved in the nitty-gritty of designing escape systems for a long time. So we have a vacuum in which the Army, Navy and Air Force do not get together with one another or with the people who are knowledgeable enough to actually resolve the problems. What Sol said is absolutely true, you cannot be innovative and design a good system while adhering to the specifications.

• *Mr. Solomonides, North American Rockwell:* I would like to see the specifications used as a guideline rather than as the final way of designing a system.

• *Mr. Atkins, Vought Aeronautics Company:* I do not believe this is an unsolvable problem. The customer will listen to what you have to say about the applicability of existing specifications and standards or the need for new ones. In fact, I have had some success in introducing my ideas into Army, Navy, and Air Force documentation. I doubt that the need for these documents will soon be eliminated. The failure of manufacturers to design systems properly is what led to the generation of standards and specifications in the first place. When the need for such documents disappears the documents themselves will disappear.

• *Mr. Stanley, Stanley Aviation Corporation:* I have listened this afternoon to at least two speakers pleading for more study programs and more data. Gentlemen, if government provides you with additional data in the form of specifications, you can look forward to a time when you will wish you did not have them. Specifications have a habit of never changing. So, a few years from now, you will find yourself shackled to specifications that may have been applicable in 1972, but will not be applicable then.

• *Mr. Kienholz, Lockheed Aircraft Corporation:* I would like to use a specification as a logical point of departure, a minimum requirement or standard to be met. However, because of the bidding environment, you cannot sell your own management or the customer on anything more than what is required to meet the specification. Although this is not right, it is the only way to survive in this business.

• *COL Till, NAECO Associates:* I think we are talking about the difference between performance specifications and design specifications. I get the impression that most of us would prefer designing a system to meet a performance specification rather than to design specification.

• *Mr. Mancinelli, Naval Air Development Center:* I agree that we want a performance specification. However, a specification that says you must design a system to have "maximum comfort," means nothing. The term maximum comfort means something different to everyone. If you have enough data to back up your performance specification, then that is what you should issue. But if you cannot define your performance parameters, you will ultimately end up with a design specification.

• *Mr. Alexander, USAF Aerospace Medical Research Laboratory:* Why doesn't this workshop recommend the formation of a life support standardization panel? A support standardization panel could accept these kinds of comments in the present state of the art and perhaps pursue it. If specifications and standards are to be kept up-to-date, we need a nucleus of people who meets periodically to update the philosophy of specifications and standards and to prepare the necessary documents for circulation throughout the industry.

• *Mr. Atkins, Vought Aeronautics Company:* The mechanism of such an organization has been created. There has been tacit agreement among the three services, the industry, and the Aerospace Industries Association to do just what you have described. But there is some difference of opinion about how effective a tri-services and industries panel would be. Some feel that such a panel would be highly effective, while others feel it would be useless because of a lack of power and authority.

WORKSHOP SUMMARY

Mr. Atkins, Vought Aeronautics Company: I am actually going to report on two activities. Twelve of us met informally yesterday evening to discuss an old, but still present, problem--human factors versus engineering design. Our ad hoc group consisted of six human factors people and six design people. From this lively discussion I drew a definite conclusion. We must function together, and I support Mr. Hebenstreit's recommendation that we must therefore be together organizationally to be 100 percent effective.

Now for the life support impact problems I will summarize the major problems and solutions that we defined in our workshop. Like the other panels, our discussions ranged over the full spectrum of our subject. The first, and one of the most important problems we discussed was the aircraft environment, or crew equipment dilemma. Crew equipment problems continue to severely degrade aircrew performance, mainly because the available personal and protective equipment is very limited in variety. Therefore, pilots must frequently wear or use equipment that is poorly suited to a particular mission or crew station configuration. For example, the F-14 and F-15, S-3A, OV-10, A-7 are worlds apart in terms of their crew complements, crew station size, duration of mission, and crew station functions. Yet the crews of these vehicles are required to wear exactly the same personal and protective equipment, and problems are bound to arise.

Many basic problems are currently inherent in the equipment: restriction of mobility and ultimately reduced effectiveness of the operator because of sheer bulk of clothing and equipment; restriction of vision and continued discomfort caused by the oxygen dispensing devices; discomfort caused by the heavy head gear and devices that are being attached to it practically daily. A fairly new and very real problem is our lack of life support requirements for multi-crew, long-duration vehicles with walk-around capability and assisted escape systems. No pilot will wear all this gear when he has a nice big hallway to walk up and down or a seat to stretch out in. All three services currently have some very active programs directed at these problems. But at the present rate of progress, we will not see solutions to most of the problems for ten or 15 years. Further, the projects do not cover the full spectrum of activities. So, we recommend that projects currently in process be expanded to cover all mission configurations and that existing projects be expedited so that final products will be available perhaps in 1975-76 instead of 1980-82.

Lack of data is a particularly important problem in the life support area. No dependable comprehensive data base exists to enable effective decisions to be made about life-support hardware needs. Basic anthropometric, physiological, and aircrew performance data are mandatory to produce mission-effective and cost-effective systems. We recognize that further study on our part will be required to work out the precise details of our data requirements.

Our workshop also addressed itself to the problems of military specifications. We concluded that existing specifications are overly restrictive, thereby stiffling innovative solutions, and that they tend to become out of date. Our group felt that a standardization panel--such as that used successfully for crew stations--should be set up for life support documentation. Such an organization, consisting of Air Force, Army, Navy, and industry representatives, could then start the painful but necessary process of document review as soon as possible.

Another potentially significant area discussed during the workshop was high-acceleration protection. Current trends in fighter aircraft philosophy indicate that sustained acceleration levels of eight to 12 Gs are right around the corner. Existing acceleration protection concepts are generally inadequate beyond a six to eight G range. We feel that objective research is needed to identify all high-acceleration protection concepts which might achieve the functional objectives of the services. One concept that has recently undergone considerable investigation is supine positioning of the pilot. It is immediately apparent that supine positioning will have a major impact on every aspect of crew station design, particularly life support equipment. The Air Force and Navy are currently working to define the physiological data required to evaluate the supine positioning concept. The Air Force is also about to begin a research program to define strength variations at high sustained G levels. In light of these events, we recommend that a series of studies be conducted to determine the impact of all high-acceleration protection concepts on life support systems. We particularly recommend that the impact of supine positioning on life support systems be investigated further. We feel that the high-acceleration studies should include the area between two and eight G in order to provide data for identifying acceleration problems in contemporary fighter-type aircraft.

The subject of crew modules received a

considerable amount of attention in our workshop. A number of potential benefits of crew modules were identified including: protection against wind blast and explosive decompression; provision for a shirtsleeve environment; and provision of a habitat for protection after reaching the earth's surface. We agreed, however, that additional study is required to define the particular benefits of the crew module and the circumstances in which crew modules will be cost effective. A current Navy Advanced Development Objective will address the overall issue of crew modules; we recommend that this activity be expedited. We also recommend that crew station designers work toward providing a shirtsleeve environment for the crew. A shirtsleeve environment is defined as the type of environment provided for the crew of commercial airlines. Until more information becomes available, we are unwilling to say that the crew module is the best way to achieve a shirtsleeve environment. But we all agree that a shirtsleeve environment should be our ultimate goal.

Perhaps our most important recommendation for the long run is that we in life support services must actively pursue truly advanced technology. An aggressive, long-range program must be defined and pursued. We now spend most of our time on yesterday's problems, not even leaving much time for today's problems. If we are ever to make genuine progress, we have to think in terms of tomorrow.

The last point we touched on at our session is, I think, highly pertinent. We have been verbally beating management about the head and shoulders. But what does management really need to know to make the decisions that we have been advocating here and in what form? This information is just as important a part of the data bank as the anthropometrical, physiological, and all the other types of data that we discussed.

EVALUATING THE COST EFFECTIVENESS OF CREW SYSTEM DESIGN

SECTION IX

COST EFFECTIVENESS AND CREW SYSTEM DESIGNS

DR. RAYMOND E. BERNBERG
LITTON SYSTEMS, INC.

Abstract: *This paper does not attempt to provide a comprehensive review of the problem of assessing the cost-effectiveness of alternative crew system designs. Rather, it reviews a cost-effectiveness analysis conducted in 1966 for the Integrated Cockpit Research program as a representative methodological approach. The major variables in the cost-effectiveness analysis were (1) automation levels, (2) crew skill, (3) displays, (4) controls, and (5) computer dispersion. This example, although an analytical abstraction of candidate avionic suites, provides a model for the analysis of cost-effectiveness of crew system design. The paper also points out several areas of needed research to better develop and refine the methodology.*

INTRODUCTION

Interest in "cost-effectiveness" peaked several years ago, when the concept was studied and applied to various military equipment systems. Today, the words are in our vocabulary but the interest in subjecting equipment and designs to cost-effectiveness assessment has waned. The reasons, I believe, are twofold. First, the problem of cost-effectiveness brings up the complexity of all the variables involved and how to deal with them. Second, the results, like all statistical analyses, become suspect or are made suspect by each vested interest.

In the first instance: "doing something about it" becomes complex, laborious, needs the "right people," and develops many arguments about what is the correct thing to do. It also becomes easier to say, "It is probably most cost-effective this way," than to try to establish cost-effective comparisons. In the second instance: when someone does not like the results, it is easy to say, "Oh, this is one of those things you can make come out anyway you want." Or, in many cases, the technique or the tools are attacked. All in all, we have a formidable bundle of reasons why we should not attempt a cost-effectiveness study.

Naturally, I do not believe these reasons justify giving up. However, we must recognize the extent of the problem at hand. Attempting to evaluate the cost-effectiveness of a crew system is a formidable task. In fact, I do not know of a case where it has been done in total.

Let us examine what a total crew system could entail.

A. Physical Variables
   1. Display equipment
   2. Control equipment
   3. Lighting
   4. Cockpit space
   5. Ejection equipment
   6. Cockpit clothing
   7. Unique data processing equipment in the crew station
   8. Life support equipment

B. Psychological Variables
   1. Skill level
   2. Training required
   3. Performance capability
   4. Workload

C. System Variables
   1. Effectiveness
   2. Reliability
   3. Level of automation
   4. Technologies level
   5. Dispersion of boxes
   6. Maintainability

Generally, a cost-effectiveness analysis compares one system with other candidate systems. The candidate systems are usually configured so that they vary in range, degree, or mechanization so that their configurations are alike except in one variable. Therefore, the figures-of-merit given the candidate systems indicate the effect of the variable. The rules would say that all candidates under consideration could meet the mission requirements at some cost. The cost-effectiveness analysis examines each candidate proposed to determine how it would be expected to perform units of the mission at the least total cost. The mission (or effectiveness) criteria would be the basis for economical treatment of the variables listed above, which would have been configured analytically to represent a spectrum of candidates. I have mentioned 18 variables in the lists above. If there were only three possible states of each variable, there would be more than 387 million possible combinations! You can see how formidable a problem this becomes if you wish to assess all possible design configurations.

How do you conduct an investigation of cost-effectiveness of crew systems? I would like to present an approach. The example is a study actually conducted on an aircraft crew system (or some aspect of the crew system) three different times and can serve as a model that could be utilized as an approach to the problem. It is a long way from being refined but it does serve as an energetic attempt to develop this methodology.

EXAMPLE STUDY 1-4

This example is taken from the Integrated Cockpit Research Program, completed in 1966 and under contract for JANAIR-ONR. The purpose of the study was to investigate the potential operator unburdening that could be accomplished in the 1975+ time frame in an aircraft by using advancements in avionic technology. An objective subsumed to this was to use cost-effectiveness criteria as a means of determining when the operator unburdening would reach the point of diminishing returns. As part of the study, and inherent in achieving the objectives, a methodology for advanced system development was organized. The cost-effectiveness portion represented an attempt to include human factors criteria within the classic cost-effectiveness methods: a step which had not been taken previously.

If you will refer back to the list of variables--physical, psychological, and system--you will remember the large number of variables which a cost-effectiveness analysis could include. This study took the approach that only certain variables, judiciously selected, can reflect the effectivity portion of the analysis. In this case, human factors data or considerations become an intrinsic part of the analysis.

This brings up the point that several approaches may be taken: (1) use all variables for effectiveness and cost; (2) assume equal effectiveness among candidates and use cost models to assess the life cycle cost as a method of comparison; and (3) use judicious selection of effectivity and hardware variables with cost models.

The first method is an intractable mess. The second method, sometimes used in support system analyses (RCA, 1967), leaves out the important differences in meeting mission criteria and mission performance. The third is what I will illustrate here. The primary variables selected for the cost-effectiveness study were: (1) automation, (2) displays, (3) controls, (4) crew skill, and (5) computer dispersion.

AUTOMATION VARIABLES

Automation level of the avionic system is defined as follows: considering each of the major avionics subsystem functions, the question is asked, "What level of crew action is required, other than monitoring, in the performance of the function?" The level is expressed as a percentile rating, with zero percent signifying that the operation is completely manual and 100 percent indicating that no crew involvement is required other than monitoring. As an example, consider the flight control function. An avionic system without an AFCS is obviously at zero percent automation insofar as automatic flight control is concerned. At the opposite extreme, an AFCS receiving all commands from a computer program, as a function of mission segment, navigation parameters, etc., is at a 100 percent level of automation.

With respect to automation level, the following subsystem functions were enumerated for the three missions of the aircraft: reconnaissance, weapons, and logistics.

1. Takeoff
2. Landing
3. Built-in self test
4. Communications
5. Engine health
6. Energy management
7. Stationkeeping
8. Flight control
9. Transition programming
10. Terrain following and avoidance
11. Navigation

In addition, for the reconnaissance and weapons missions, the level of automation for specific reconnaissance and weapon functions is also considered. The automatic level progress is as follows. Level A1 is representative of. roughly speaking, an ILAAS, or IHAS

level of complexity. For example, landing and takeoff are largely manual operations, the crew receiving landing aid from ILS and carrier landing systems. Built-in self-test checks are automatic for nearly all avionic subsystems, but mode selection is largely manual.

Communications involve crew selection of band, channel, etc., while the data processing stylizes the message. Engine health requires significant crew monitoring and control functions. Similar comments are appropriate for the remaining variables (see Table 1 and Figures 1 and 2).

The overall average automation levels for the transport, reconnaissance, and weapons missions are respectively: 57.5 percent, 50.8 percent, and 60.8 percent.

System A2 level is increased in automation in only one category from A1: built-in self-test and mode switching are increased to a 70 percent level. At this level of automation, mode selection is automatic with mission segment. However, under a failure condition, an alternate mode selection must be made manually.

Similarly, in the remaining levels, only one subsystem category is increased in automation degree at each step. This progression is continued through A16. For a description of the change occurring at each level, see Table 2.

DISPLAY VARIABLES

Five display sophistication levels were defined consisting of different numbers of primary and auxiliary displays. Figure 2 shows the number and arrangement in the cockpit of each of the display candidates, D1 through D5. Note that a primary display may take the form of a head-up, horizontal, or multisensor display. The auxiliary displays are shown by the cross-hatched symbol.

CONTROL VARIABLES

Seven levels of control sophistication were defined (see Table 3). Differences in control levels are only in duplication of controls for the two-man crew, not in mechanical improvement of any control hardware. Also each control level differs from its neighbors by the duplication of only one additional hardware item.

CREW SKILL VARIABLES

Three levels of crew skill were defined at a conceptual level: low, average, and high. Any large group of men can be trained and rated on its capability for performing crew functions in military aircraft. In other words, it is possible to take any large group and divide it into a top third, a middle third, and a lower third skill level. A study of the effect of crew skill levels on the cost-effectiveness performance of each of the three missions may indicate how to allocate crews of various skill levels more efficiently over the missions. Such a study may help to determine if the superior crews should be used for logistics, weapons, or reconnaissance. It is assumed that military commanders can arbitrarily assign a crew of any skill level to any of the missions; however, this leaves only crews of the nonassigned skill levels available for other missions.

For this study variable no extra costs were charged against an aircraft system with a highly rated crew. It was assumed that the allocation of crews can be charged as a commander desires and that the training budget could best be charged equally against each aircraft.

COMPUTER DISPERSION VARIABLES

The three different computer dispersion levels are defined in Figure 3. For the weapons and reconnaissance missions at least one extra computer box is added for each segmentation level to handle the extra load. It is pointed out that whether the whole computational task is divided in four segments or ten segments should be completely independent of the actual level of complexity of that whole computational task (or automation level). For instance, the most complex automation level, A16, can be divided among ten boxes or four boxes (or one "central" box, for that matter), and so can the simplest automation level, A1.

CANDIDATES FORMED FROM VARIABLES

The five variables, with a total of 34 discrete levels, are summarized in Table 4. These 34 discrete levels can be combined into 5,040 different, yet complete, candidates (16 x 7 x 5 x 3 x 3 = 5,040). As a practical number of alternatives to study, 102 candidates were chosen. This choice allows three plots over the full range of each variable in the final results (3 x 34 = 102). Three runs over each variable allow one run where the other variables are held fixed at their lowest levels, one run where the other variables are held fixed at an intermediate level, and one run where the other variables are held fixed at their highest level. Thus, by only 102 candidates, all of the possible 5,040 points are bracketed because of the high and low level runs.

The candidates are identified in the original report (Bernberg, et al., 1967b) which lists the 102 combinations of the five variables. The major part of each aircraft

TABLE 1

DESCRIPTION OF THE 16 AUTOMATION LEVELS

AUTOMATION LEVEL	CREW LOAD WEIGHTINGS FOR AUTOMATION														
	75	8	7	5	7	10	3	10	5	10	10	25	100	25	100
												RECON		WEAPONS	
LEVEL I.D. CODE	LOGISTICS AVE.	TAKEOFF AND LAND	BIST AND MODE SWITCHING	COMMUNI-CATIONS	ENGINE HEALTH	ENERGY MANAGE-MENT	STATION-KEEPING	FLIGHT CONTROL	TRANSI-TION PROGRAM	TF AND TA	NAVI-GATION	EXTRA	AVE.	EXTRA	AVE.
A1	43.3/75	30%	50	50	40	50	70	85	70	70	60	30	50.8/100	70*	60.8/100
A2	44.7/75	30	70	50	40	50	70	85	70	70	60	30	52.2/100	70	62.2/100
A3	45.4/75	30	70	50	40	50	70	95	70	70	60	30	53.2/100	70	63.2/100
A4	47.6/75	30	70	50	70	50	70	95	70	70	60	30	55.3/100	70	65.3/100
A5	47.6/75	30	70	50	70	50	70	95	70	70	60	50	60.3/100	70	65.3/100
A6	51.2/75	30	70	50	70	50	70	95	70	70	95	50	64.1/100	72	69.1/100
A7	54.2/75	30	70	50	70	50	70	95	70	95	95	50	66.6/100	70	71.6/100
A8	54.8/75	30	70	50	70	50	70	95	95	95	95	50	67.8/100	70	72.8/100
A9	54.8/75	30	70	50	70	50	70	95	95	95	95	70	72.5/100	70	72.5/100
A10	55.7/75	30	70	50	70	50	95	95	95	95	95	70	72.4/100	70	52.4/100
A11	60.7/75	30	70	50	70	95	95	95	95	95	95	70	78.9/100	70	78.9/100
A12	61.8/75	30	70	50	95	95	95	95	95	95	95	70	79.6/100	70	79.6/100
A13	63.0/75	30	70	95	95	95	95	95	95	95	95	70	81.3/100	70	81.3/100
A14	64.2/75	30	95	95	95	95	95	95	95	95	95	70	83.0/100	70	83.0/100
A15	69.8/75	95	95	95	95	95	95	95	95	95	95	70	88.6/100	70	88.6/100
A16	75 /75	100	100	100	100	100	100	100	100	100	100	100	100	100	100

*Automation level of weapon functions

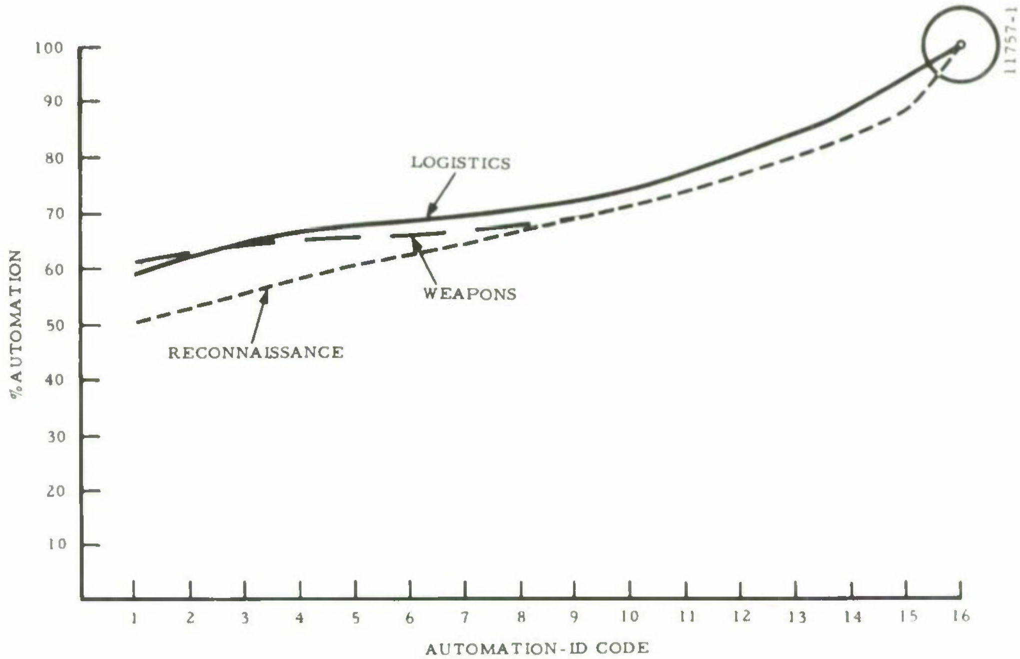

Figure 1. System automation levels.

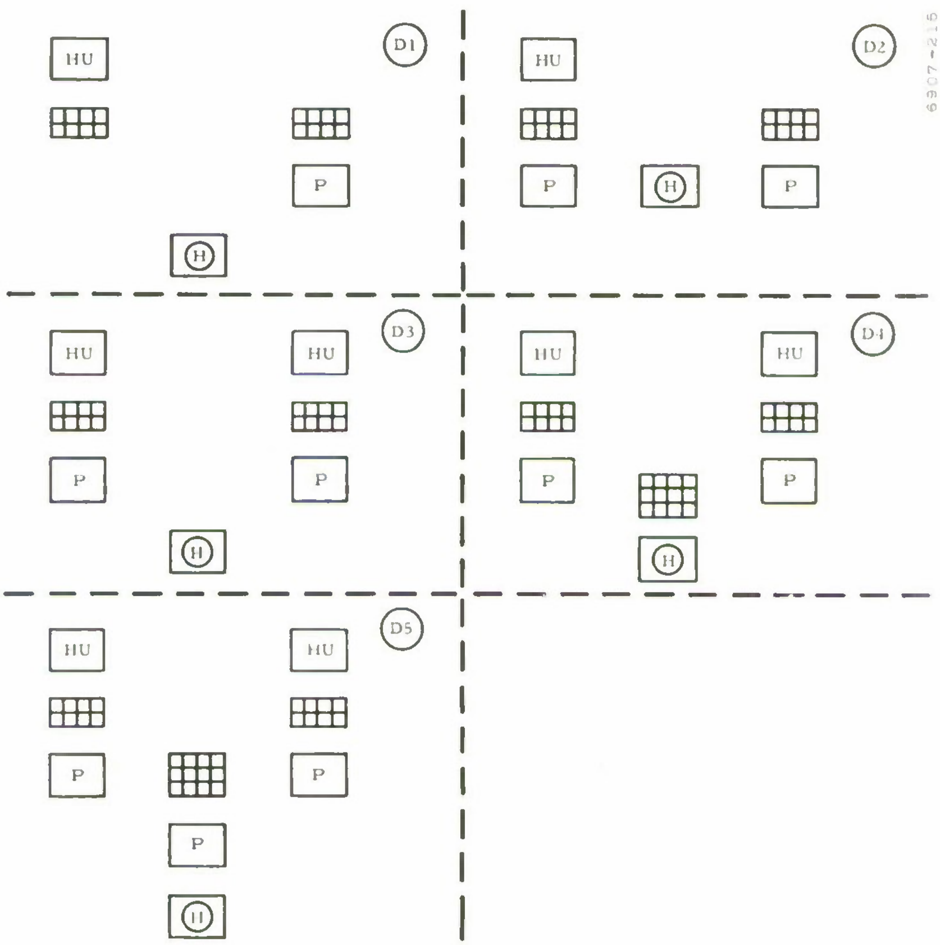

Figure 2. Description of the five display sophistication levels.

TABLE 2

DESCRIPTION OF THE 16 AUTOMATION LEVELS--A DETAILED VIEW

LEVEL	AUTOMATION CHANGE
A1	APPROXIMATELY ILAAS LEVEL SYSTEM (SEE TABLE 1).
A2	BUILD IN SELF TEST AND MODE SELECTION AUTOMATION INCREASED FROM 50% TO 70%. THIS PERMITS AUTOMATIC MODE SELECTION BY DATA PROCESSING EXCEPT UNDER FAILURE CONDITIONS.
A3	FLIGHT CONTROL AUTOMATION INCREASED FROM 85% TO 100%. FLIGHT MODE SPEED AND ALTITUDE ARE AUTOMATICALLY SELECTED BY THE APPROPRIATE PROGRAMS KEYED TO MISSION SEGMENT.
A4	ENGINE HEALTH AUTOMATION IS INCREASED FROM 40% TO 70%. ENGINE PARAMETERS ONLY DISPLAYED TO CREW WHEN PROBLEM EXISTS OR REQUESTED. DATA PROCESSING MONITORS ALL ENGINE PERFORMANCE QUANTITIES.
A5	RECONNAISSANCE AUTOMATION IS INCREASED FROM 30% TO 50%. THE RECONNAISSANCE FLIGHT PLAN IS NOW FLOWN AUTOMATICALLY.
A6	NAVIGATION AUTOMATION IS INCREASED FROM 60% TO 100%. COMPLETELY INTEGRATED NAVIGATION SYSTEM NOW PROVIDES MULTIPLE DISTINCTIONS USING AREA LORAN, TACAN, AND VOR TOGETHER WITH SELF-CONTAINED NAVIGATION AIDS.
A7	TERRAIN FOLLOWING AND AVOIDANCE AUTOMATION INCREASED FROM 70% TO 100%. AUTOMATIC TERRAIN AVOIDANCE IS NOW INTRODUCED (IN ADDITION TO AUTOMATIC TERRAIN FOLLOWING.
A8	TRANSITION PROGRAMMING IS NOW COMPLETELY AUTOMATED, REQUIRING ONLY PILOT MONITORING.
A9	RECONNAISSANCE AUTOMATION IS INCREASED TO 70%. ALL SENSORS ARE SELECTED, AIMED AND THEIR DATA DISPLAYED AND TRANSMITTED WITHOUT OPERATOR INTERVENTION.
A10	STATIONKEEPING AUTOMATION IS INCREASED TO 100%. IN THE STATIONKEEPING MODE, AIRCRAFT STATION IN THE FLIGHT FORMATION IS NOW AUTOMATICALLY MAINTAINED ON THE BASIS OF PROCESSED "FOLLOW-THE-LEADER" COMMANDS.
A11	ENERGY MANAGEMENT AUTOMATION IS NOW INCREASED TO 100%. ENDURANCE LIMITS AND MAXIMUM RANGE VERSUS FLIGHT PROFILES ARE AUTOMATICALLY COMPUTED AND DISPLAYED TO CREW ONLY IF REQUIRED.
A12	ENGINE HEALTH MONITORING IS NOW COMPLETELY AUTOMATED. ONLY CAUTION OR WARNING INFORMATION IS DISPLAYED TO CREW.
A13	COMMUNICATIONS AUTOMATION IS INCREASED TO 95%. SELECTION OF BANDS, CHANNELS, MONITORING FOR JAMMING AND TRANSMISSION OF ALL REQUIRED MISSION DATA IS AUTOMATICALLY PERFORMED. SOME VOICE MESSAGES TRANSMITTED.
A14	BUILT-IN SELF-TEST AND MODE SWITCHING COMPLETELY AUTOMATED BOTH FOR NORMAL AND CONTINGENCY SITUATIONS.
A15	LANDING IS NOW A FULLY AUTOMATIC FUNCTION, REQUIRING ONLY CREW MONITORING, AND TAKEOFF IS AUTOMATIC EXCEPT FOR A MANUAL ACTUATION.
A16	RECONNAISSANCE FUNCTIONS ARE FULLY AUTOMATED TO INCLUDE AUTOMATIC TARGET DETECTION. LIKEWISE, WEAPON DELIVERY IS FULLY AUTOMATIC INCLUDING AUTOMATIC DETECTION, THREAT CLASSIFICATION, AND FIRING ON TARGETS. THE MAIN CREW FUNCTIONS ARE INITIATION OF TAKEOFF AND GENERAL MONITORING.

TABLE 3

DESCRIPTION OF THE SEVEN CONTROL LEVELS

HARDWARE ITEMS	I. D. CODES OF CONTROL VARIABLES						
	L1	L2	L3	L4	L5	L6	L7
SENSOR CONTROL SETS	1	1	1	1	1	2	2
A/N ENTRY SETS	1	1	1	1	2	2	2
COMPUTER ACCESS SETS	1	2	2	2	2	2	2
CURSOR SETS FOR DISPLAYS	1	1	1	2	2	2	2
WHEEL AND COLUMN SETS	1	1	2	2	2	2	2
WEAPON CONTROL SETS	1	1	1	1	1	1	2

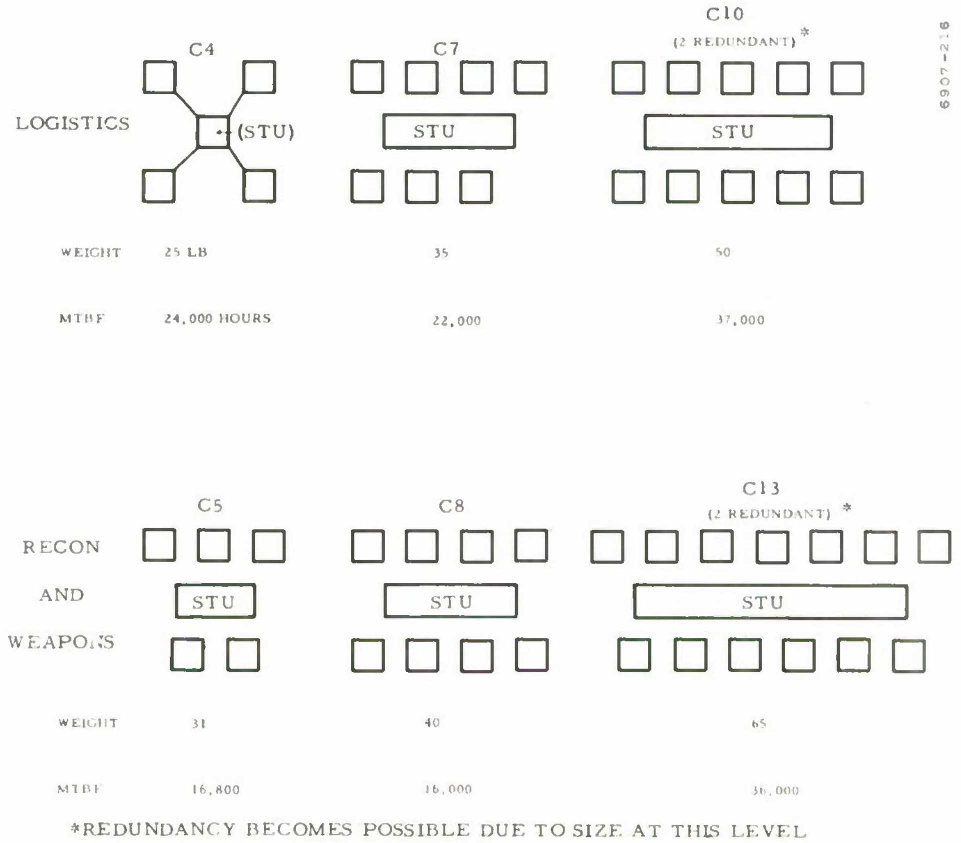

Figure 3. Description of the three computer dispersion levels.

TABLE 4

SUMMARY OF THE STUDY VARIABLES AND THEIR DISCRETE LEVEL

	AUTOMATION, 16 LEVELS	A1, A2, A3...A16
MAN-MACHINE VARIABLES	CREW SKILL, 3 LEVELS	S1, S2, S3
	CONTROLS, 7 LEVELS	L1, L2...L7
HARDWARE VARIABLES	DISPLAYS, 5 LEVELS	D1, D2...D5
	COMPUTER DISPERSION, 3 LEVELS	LOGISTICS: C4, C7, C10 RECONNAISSANCE WEAPONS: C5, C8, C13

system was held constant over the 102 systems. The 102 systems were identified by listing their only distinguishing differences--the state of each of the five variables.

Actually, there were 102 candidates for *each* of the three missions. Each of the missions had a different basic aircraft that was constant over its 102 candidates.

CONDUCTING THE ANALYSIS

The cost-effectiveness analysis was pursued, for the most part, in a standard manner. The mathematical model was based on the usual mission-oriented criteria. And as in the customary approach, candidate systems were selected, data were gathered on each candidate to feed the equation, and the more cost-effective systems were noted from the calculations.

However, the peculiar accomplishment of this work, and we believe this was the first time it has been attempted, is that the cockpit-operator-avionic system variables have been related to economical mission accomplishment. Thus the particular candidate systems chosen for comparison, and hence the data used in the cost-effectiveness equation and the results, all reflect major human factor effects. Automation levels and display-control sophistication along with the intimately related man-machine interactions in the cockpit during combat are compared and judged according to standard mission-oriented cost-effectiveness criteria, rather than according to a subcriterion such as crew unburdening, or crew comfort. Of course, all of these items were considered--automation level, display and control sophistication, crew unburdening, etc.--but they are not considered good, per se. Only to the extent that they increase the number of units of mission accomplishment per million dollars are they valued and selected.

General steps in the cost-effectiveness methodology are reviewed in Figure 4. Previous steps have involved a mission analysis and technology studies extrapolated into the time frame of interest. With this background, a series of alternate mechanizations can be defined for a cost-effectiveness comparison.

In an unconstrained cost-effectiveness study of a typical system, an infinite number of variables defining alternate systems could be compared. Typical variables for tactical aircraft include speed, required takeoff space, payload, range, maneuverability, maintenance, logistics, turnaround alternatives, sensors, accuracies, costs, reliabilities, cockpit controls, displays, automation, crew number, skills, and deployment strategies. For practical reasons, the scope of the study is narrowed down in the statement of the problem so that all of the infinite number of variables except a specified few, are held constant at reasonable expected values. This set of specified few are the study variables of the program. A major step in refining the problem is the naming of these specific variables (and thereby fixing all others at reasonably expected values) and the ranges over which changes will be considered.

The variables selected for study in the program have been identified. The methodology for selecting the three variables was inherent in the basic objectives of the program. A primary objective of the program was to use advanced avionics to unburden the operator and improve mission performance. The level of automation was inversely related to operator unburdening since automating additional functions serves to reduce pilot workload; therefore, one of the major variables to be manipulated in the cost-effectiveness appraisal is the level of automation. The choice of the controls and displays variables stems from the operator unburdening aim and are included for the rather obvious reason that they provide the interface between the operator, the avionic system, and the external mission situation. With respect to the digital processor, size and cost are most strongly influenced by the level of automation. In

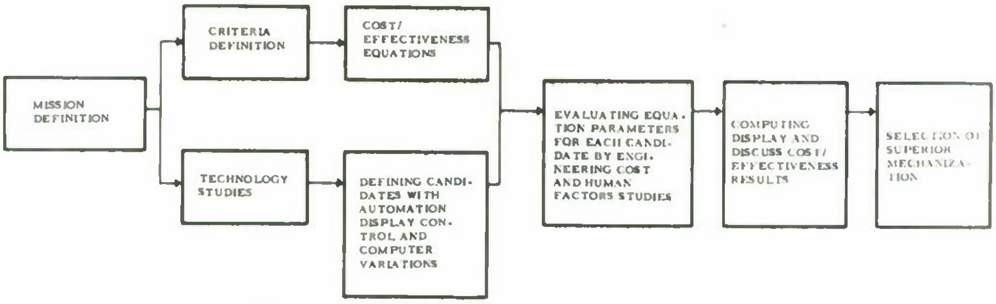

Figure 4. Cost-effectiveness task sequence.

addition, different modulating levels (e.g., computer dispersion) are considered as a separate item.

FORMING CANDIDATES BY COMBINING VARIABLES INTO COMPLETE SYSTEMS

The system cost-effectiveness analysis compares one total system against another total alternate system, not one subsystem against another black box. The total system candidates may differ only in one subsystem (the variable for tradeoff), but this subsystem difference is compared by its effect in the total picture or total system. Thus, candidate mechanizations are formed for comparison by varying the avionic system to create a number of complete systems. Any one of these systems may be able to perform the mission at some cost. The cost-effectiveness analysis examines each candidate proposed to see which is expected to perform units of the mission at the least total cost.

SPECIFY THE COST-EFFECTIVENESS DECISION CRITERIA

The tools can now be developed to compare the alternatives. A complete and practical mission description should have within it the criteria for judging the candidates proposed. The criterion is a statement of a central composite decision item to be computed for each candidate. A criterion statement is usually in terms of economical accomplishment of essential units of the mission. For example, a logistics mission criterion may be "the expected number of ton-miles accomplished until shot down per million dollars of total lifetime costs."

The essential units of the job are "ton-miles," or amount of material transported a certain distance, and a survivability expressed as "expected until shot down." The economy of doing the job is reflected in "per million dollars of total lifetime costs." This criterion statement identifies a consistent yardstick by which each candidate will be measured and judged in an absolute sense or compared relative to alternate systems. A different criterion is formulated to represent each mission. Typical cost-effectiveness criteria are displayed in Table 5.

TABLE 5

CRITERIA DEFINED FOR THE MISSIONS

ICRP MISSIONS	COST-EFFECTIVENESS CRITERIA
LOGISTICS	THE EXPECTED NUMBER OF TON-MILES ACCOMPLISHED UNTIL SHOT DOWN, PER MILLION DOLLARS OF TOTAL LIFETIME COSTS
RECONNAISSANCE	THE EXPECTED NUMBER OF AVERAGE TARGETS SUCCESSFULLY ACQUIRED UNTIL SHOT DOWN, PER MILLION DOLLARS OF TOTAL LIFETIME COSTS
WEAPONS	THE EXPECTED NUMBER OF AVERAGE TARGETS DESTROYED UNTIL SHOT DOWN, PER MILLION DOLLARS OF TOTAL LIFETIME COSTS

DEVELOPING COST-EFFECTIVENESS EQUATIONS

The figure-of-merit equations are written to match the decision criteria so that the proper factor is computed for each candidate system. If the criteria state the economics of performing the job, then the equation should express that exactly.

Each item in the criterion statement is represented by a parameter in the equation. Typical parameters are cost, survivability, destruction probability, etc. The units of the main cost-effectiveness figure-of-merit equation should be identical to the criteria. Often, these units have a very practical meaning. Typical equations are shown in Table 6.

If required by expected data inputs or study variables, the parameters are themselves expressed by a combination of mathematical factors and expressions. For example, the total system cost may include one base cost term reflecting the constant hardware and personnel of each specific candidate. Other typical submodels are shown in Tables 7 and 8.

TABLE 6

MAIN MATH MODELS

CRITERIA	EQUATIONS	DEFINITIONS
TON-MILES SURVIVED PER MILLION DOLLARS	$\frac{N_f T_M}{C_L}$	N_f = MEAN NUMBER OF FLIGHTS SURVIVED T = AVERAGE TONNAGE TRANSPORTED PER FLIGHT M = AVERAGE FLIGHT LENGTH C_L = TOTAL 10-YEAR COSTS PER AIRCRAFT
SUCCESSFUL TARGET ACQUISITION SURVIVED PER MILLION DOLLARS	$\frac{N_r R}{C_R}$	N_r = MEAN NUMBER OF RECONNAISSANCE TARGETS SURVIVED R = SUCCESSFUL ACQUISITION PROBABILITY, ON AVERAGE TARGET C_R = TOTAL 10-YEAR COSTS PER RECONNAISSANCE AIRCRAFT
KILLS SURVIVED PER MILLION DOLLARS	$\frac{N_t D}{C_W}$	N_t = MEAN NUMBER OF TARGETS ATTACKED AND SURVIVED D = DESTRUCTION PROBABILITY ON AVERAGE TARGET C_W = TOTAL 10-YEAR COSTS PER WEAPONS AIRCRAFT

TABLE 7

SURVIVABILITY SUBMODEL

SURVIVABILITY WAS ANALYZED INTO ENEMY AND CRASH-CAUSED VARIABLES FOR HUMAN FACTORS INPUTS

$$\nu_f, N_r, N_t = \frac{1}{\frac{1}{N_e} + \frac{1}{N_c}} \qquad N_e = N_{ec} E_{AS} E_{DS} E_{LS} \qquad N_c = N_{co} C_{AS} C_{DS} C_{LS}$$

	N_e	= MEAN NUMBER OF FLIGHTS SURVIVED AGAINST ENEMY ACTION ONLY
	N_c	= MEAN NUMBER OF FLIGHTS SURVIVED AGAINST CRASH ONLY
	N_{eo}	= BASE VALUE OF N_e
	N_{co}	= BASE VALUE OF N_c
HUMAN FACTORS JUDGMENTS	E_{AS}	= IMPROVEMENT FACTOR DUE TO AUTOMATION AND CREW SKILL LEVELS FOR SURVIVABILITY AGAINST ENEMY ACTION
	E_{DS}	= IMPROVEMENT FACTOR DUE TO DISPLAY AND CREW SKILL LEVELS FOR SURVIVABILITY AGAINST ENEMY ACTION
	E_{LS}	= IMPROVEMENT FACTOR DUE TO CONTROL AND CREW SKILL LEVELS FOR SURVIVABILITY AGAINST ENEMY ACTION
	C_{AS}, C_{DS}, AND C_{LS}	= IMPROVEMENT FACTORS, AS ABOVE, FOR SURVIVABILITY AGAINST CRASH

TABLE 8

SUCCESS PROBABILITY SUBMODEL

SUCCESS PROBABILITY WAS FACTORED DIRECTLY INTO HUMAN FACTOR INPUT DATA

$$R = R_o f_{AS} f_{DS} F_{LS}$$

$$D = D_o f_{AS} f_{DS} f_{LS}$$

HUMAN FACTORS JUDGMENTS:

- R_o AND D_o BASE VALUES OF R AND D
- f_{AS} = IMPROVEMENT FACTOR DUE TO AUTOMATION AND CREW SKILL LEVELS FOR PROBABILITY OF SUCCESS
- f_{DS} = IMPROVEMENT FACTOR DUE TO DISPLAYS AND CREW SKILL LEVELS FOR PROBABILITY OF SUCCESS
- f_{LS} = IMPROVEMENT FACTOR DUE TO CONTROLS AND CREW SKILL LEVELS FOR PROBABILITY OF SUCCESS

EVALUATING DATA FOR EACH CANDIDATE AND THE SOURCES

The complete list of parameters and factors in the main mathematical model and the submodels identifies the necessary and sufficient amount of data required on each candidate to perform the cost-effectiveness computations. Time, money, and talent need not be wasted producing extraneous data not pertinent to economical mission performance. This step in the methodology of "measuring" each candidate in its essential dimensions is illustrated in Figure 5.

Each item in the equations must be supplied by some means. These data inputs are estimates of expected real-life probability of mission success, survivability, and costs. Thus, they are not theoretical or incomprehensible in any way, and are very amenable to experimental evaluation. Data sources may vary from live tests (which are most accurate, but very expensive) on down to the best professional judgments (which are least accurate, but least expensive).

Cost-effectiveness results, because they are estimates of practical quantities, could be verified by actual field trial. This would mean full development, procurement, and employment in a Vietnam type war of statistically significant members of aircraft of *each* candidate type. For example, with three automation levels, two display and control levels, and two crew skill levels for each of three missions, there are 36 (3 x 2 x 2 x 3) candidate aircraft types. If ten aircraft of each

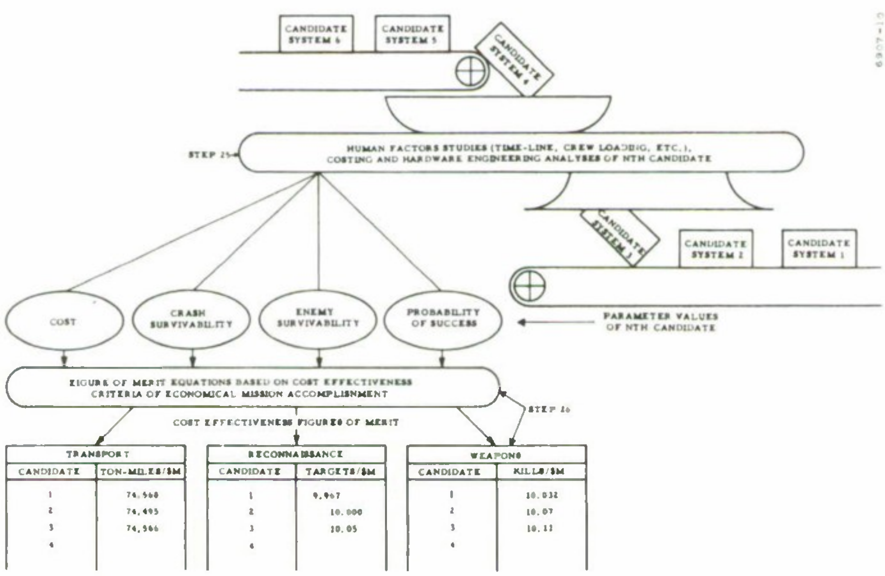

Figure 5. Cost-effectiveness evaluation.

type were sufficient for the field test, then about 1.8 billion dollars would be required for the 360 aircraft at five million dollars each.

This is the ideal verification, but impractical. In fact, the major purpose of cost-effectiveness studies is to substitute for such a live test and get estimates of these same performance quantities at a fraction of the cost.

Live laboratory tests are almost identical to the above in costs, but deployment is made over a training course instead of in actual war. The probability of success results is rather good, but the survivability data may be weak. This type of full-scale test for almost 1.8 billion dollars is usually impractical.

An experimental method can be a static or dynamic simulation of a full-sized "working" cockpit. The alternate equipment (different automation levels, different number of displays, and varying numbers of cockpit controls) and personnel can be placed in the basic frame for comparison tests. Costs for such a program can vary from 200 thousand to several million dollars. It is possible in some cases to justify this several million dollar expenditure to help optimize an aircraft subsystem (cockpit) when hundreds of the aircraft will be deployed at total lifetime costs in the billions because tens of millions of dollars are saved for each one percent system cost-effectiveness improvement.

Another source of data that can be used for cost-effectiveness appraisal is experimental literature bearing on the factors under consideration. There are many studies in the literature comparing aircraft flight performance with varying kinds of displays, in addition to varying control configuration. Due to the control problems inherent in experimental methodology, it is often found that major differences exist between studies, and the experimental results are largely restricted to the kind of conditions present in the particular situation. It is this area of identifying the relevant points and determining what features can be applied to a different situation that relies heavily upon the expertise of the analyst.

Combat records of a variety of pilots, aircraft, and cockpit mechanizations may also be examined. The effectiveness of performance as a function of differences in crew skill, display or control sophistication, and automation level may be sought by careful cross examination of differences to cancel out unwanted variables such as aircraft speed, turn radius, weapon variations, and target and enemy environment differences. The resulting data would then be extrapolated into the military and hardware time frame of interest. Data for N_{eo}, N_{co}, R, and D may be obtained in this manner. This data-gathering technique can be tedious, time consuming, and of limited value if the extrapolations required are too great. Nevertheless, even one or two reasonably established data points can be very important to an analysis that otherwise rests only on professional judgments.

DATA EMPLOYED

The data required can be estimated directly by professionals who have extensive experience in the system development and evaluation process and are able to extrapolate their knowledge into the desired framework. Data for E_{AS}, E_{DS}, E_{LS}, C_{AS}, C_{DS}, C_{LS}, f_{AS}, f_{DS}, and f_{LS} may be obtained by this method.

An important methodological consideration in using professional estimates is to structure the situation in such a way that judgments are obtained on the major variables individually. More specifically, the judge is provided with a baseline configuration. An alternate system containing one major change, such as the inclusion of a second primary display at the reconnaissance station, is given to the judge and he is asked to estimate the percentage improvement of the new display configuration over the baseline configuration. The estimates are obtained in terms of the three major parameters in the study--that is, survivability against crashes, survivability against an enemy environment, and mission success probability.

In other words, it is possible to ask an individual in a systematic fashion to estimate the effect of any variety of control and display configuration on the accomplishment of the mission. It is these kinds of data that make what we believe is a unique contribution to the classical cost-effectiveness equation.

Data may be sought defining the average or mean values of the expected operating point identified in the mission descriptions. This may include the average enemy environment, the average weather environment, and the expected operational strategies. More significance and safety are secured in the results when statistical values are obtained so that, in addition to the expected values, the variance and the extreme variations or limits are estimated. Obviously, a peculiar candidate, designed to be superior only at the expected values but which fails completely in other conditions, is an extremely risky weapon system where the enemy may choose the battle conditions.

PLANNING SENSITIVITY STUDIES ON CRITICAL PARAMETERS

The data gathering and equations together should indicate parameters and terms whose accuracy is essential or values are in doubt. On these critical parameters, data points can be selected above and below the expected operating point for calculations which reveal the effect of inaccuracy or variable environmental conditions on the entire results. Conclusions can be drawn from these sensitivity results indicating the refinement required at evaluating the critical parameters.

COST SUBMODEL

The total cost submodel is formed by adding increments corresponding to the four hardware variable areas to a base aircraft system expense. All costs in the equation represent the total development, procurement, and operational costs incurred over the total development life, estimated at ten years. Consistent with the accuracy of the other data and for simplicity, all ten-year total costs were obtained by estimating the procurement cost of the item in quantities of about 200 and multiplying by 3.5. This factor, 3.5, was obtained by estimating the average operational cost per year of each item as 25 percent of the procurement cost. Thus, any ten-year total cost is 1 + 10 (0.25) = 3.5 times the particular procurement cost. The cost submodel details and definitions are all in Table 9. Data for these cost submodels were estimated and extrapolated from present hardware complexity and parts counts.

EVALUATING DATA FOR EACH CANDIDATE

Each factor and term defined in the mathematical models must be evaluated for each candidate. The effectiveness values are given first, followed by the cost values.

For each man-machine variable the best systems and the poorest systems were identified. The poorest systems were rated 1.00 and the best systems were rated with respect to 1.00. These ratios, called the peak relative values, are listed in Table 10. Also, an optimistic and a pessimistic value of each peak relative value are listed for the sensitivity calculations.

Once the effectiveness improvement from the poorest to best values of the man-machine variables was estimated, then all intermediate values were apportioned by the raters. These values, all given relative to the poorest in mission effectiveness, were assigned by the raters in the format shown in Table 11.

Cost data inputs for $C_{LA}(AN,CQ)$, $C_{RA}(AN,CQ)$, and $C_{WA}(AN,CQ)$ of Table 10 are given in Table 12. Control and display costs are listed in Table 13.

The detailed results of the cost-effectiveness analysis are given in the original report of the study (Bernberg, et al., 1967b). The separate effects of each study variable (automation, displays, controls, and computer dispersion) on the total aircraft system cost-effectiveness can be plotted from

TABLE 9

TOTAL PROCUREMENT AND TEN-YEAR OPERATIONAL COSTS SUBMODELS

	TOTAL PER AIRCRAFT	ALL AIRCRAFT EXCEPT ITEMIZED AVIONICS	BASIC* AUTOMATION	AUTOMATION COMPUTERS	DISPLAYS	CONTROLS	AMMUNITION
LOGISTICS	C_L =	8.75**	$+ 1.0 + \left(\frac{N+2}{100}\right)$	$= C_{LA}(AN,CQ) +$	$C_D(DM)$	$+ C_{LL}(LP)$	
RECON	C_R =	7.00**	$+ 1.0 + \left(\frac{N+2}{100}\right)$	$= C_{RA}(AN,CQ) +$	$C_D(DM)$	$+ C_{RL}(LP)$	
WEAPONS	C_W =	5.25**	$+ 1.0 + \left(\frac{N+2}{100}\right)$	$= C_{WA}(AN,CQ) +$	$C_D(D_M)$	$+ C_{WL}(LP)$	$+ (0.01)\frac{1}{2}N_t$**

VARIABLES: AUTOMATION--AN, N = 1, 2, ..., 16
CONTROLS--LP, P = 1, 2, ..., 7
DISPLAYS--DM, M = 1, 2, 3, 4, 5
COMPUTER DISPERSION--CQ, Q = 4, 7, 10 (LOGISTICS)
Q = 5, 8, 13 (RECON AND WEAPONS)

*When N = 16, the basic automation costs are 1.32 M, not 1.18 M. All costs represent the total ten-year expense and are in units of millions of dollars.

**These estimates were obtained from the operations research groups at Lockheed Aircraft and North American Rockwell.

TABLE 10

PEAK RELATIVE VALUES OF THE ICRP MAN-MACHINE VARIABLES

		CUMULATIVE PEAK RELATIVE VALUES	DISTRIBUTED PEAK RELATIVE VALUES OF ICRP MAN-MACHINE VARIABLES		
			AUTOMATION AND CREW SKILL	CONTROLS AND CREW SKILL	DISPLAYS AND CREW SKILL
	DISTRIBUTION	100%	60%	15%	25%
EFFECTIVENESS PARAMETERS	SURVIVABILITY AGAINST CRASHES	α	C_{AS} (MAX)	C_{LS} (MAX)	C_{DS} (MAX)
		1.000000	1.00000	1.000	1.00000
		2.006004	1.48678	1.122	1.20252
		6.047640	2.59600	1.400	1.66400
	SURVIVABILITY AGAINST CRASHES	β	E_{AS} (MAX)	E_{LS} (MAX)	E_{DS} (MAX)
		1.00000	1.000000	1.000000	1.00000
		1.25068	1.141295	1.035232	1.05872
		1.76083	1.385000	1.096000	1.16000
	MISSION SUCCESS PROBABILITY	γ	f_{AS} (MAX)	f_{LS} (MAX)	f_{DS} (MAX)
		1.0000	1.000000	1.000000	1.000000
		1.5083	1.269988	1.067648	1.112948
		1.9200	1.447000	1.112000	1.187000

EQUATIONS: $\alpha = C_{AS}\text{ (MAX)} \cdot C_{LS}\text{ (MAX)} \cdot C_{DS}\text{ (MAX)}$

$\beta = E_{AS}\text{ (MAX)} \cdot E_{LS}\text{ (MAX)} \cdot E_{DS}\text{ (MAX)}$

$\gamma = f_{AS}\text{ (MAX)} \cdot f_{LS}\text{ (MAX)} \cdot f_{DS}\text{ (MAX)}$

DEFINITION: Each peak relative value is the estimated ratio of effectiveness performance of the best man-machine system to the poorest man-machine system in terms of assigned average ratings.

NOTE: The middle value in each box is the expected operating point, and the high and low values are for sensitivity calculations about that operating point.

TABLE 11

FORMAT FOR ESTIMATING THE RELATIVE INFLUENCE OF MAN-MACHINE VARIABLES ON MISSION EFFECTIVENESS

			MISSION EFFECTIVENESS PARAMETERS								
			RELATIVE SURVIVABILITY AGAINST CRASHES			RELATIVE SURVIVABILITY AGAINST ENEMY			RELATIVE MISSION SUCCESS PROBABILITY		
CREW SKILL LEVEL			S1	S2	S3	S1	S2	S3	S1	S2	S3
ICRP MAN-MACHINE VARIABLES	AUTOMATION	A1 A2 . . . A16									
	CONTROLS	L1 L2 . . . L7									
	DISPLAYS	D1 D2 D3 D4 D5									

TABLE 12

COMPUTER TOTAL TEN-YEAR COSTS AS A FUNCTION OF DISPERSION, MISSION, AND AUTOMATION

COMPUTER DISPERSION / AUTO LEVEL	LOGISTICS: $C_{LA}(AN,CA)$			RECONNAISSANCE: $C_{RA}(AN,CQ)$			WEAPONS: $C_{WA}(AN,CQ)$		
	C4[1]	C7	C10	C5	C8	C13	C5	C8	C13
A1[2]	0.110457[3]	0.130183	0.142839	0.161987	0.174521	0.192843	0.193876	0.208877	0.230804
A2	0.140553	0.165651	0.181759	0.166450	0.179330	0.198156	0.198338	0.213686	0.236116
A3	0.145271	0.171213	0.187589	0.171234	0.184485	0.203851	0.203851	0.218838	0.241812
A4	0.151876	0.178994	0.196396	0.177930	0.191699	0.211824	0.209818	0.226055	0.249785
A5	0.151876	0.178894	0.196396	0.193876	0.208877	0.230804	0.209818	0.226055	0.249785
A6	0.164451	0.193816	0.212660	0.206630	0.222618	0.245987	0.222572	0.239796	0.264968
A7	0.173884	0.204936	0.224861	0.216195	0.232925	0.257376	0.232138	0.250103	0.276357
A8	0.178602	0.210494	0.230958	0.220980	0.238077	0.264600	0.236922	0.255255	0.282048
A9	0.178602	0.210494	0.230958	0.236922	0.255255	0.282048	0.236922	0.255255	0.282048
A10	0.181430	0.213829	0.234619	0.239792	0.258346	0.285467	0.239792	0.258346	0.285467
A11	0.197152	0.232358	0.254947	0.255766	0.275524	0.304448	0.255766	0.275524	0.304448
A12	0.203756	0.240142	0.263487	0.262430	0.283889	0.312417	0.262430	0.283889	0.312417
A13	0.210676	0.248294	0.272433	0.269766	0.290640	0.321150	0.269766	0.290640	0.321150
A14	0.217592	0.256449	0.281379	0.276143	0.297511	0.328741	0.276143	0.297511	0.328741
A15	0.235200	0.277200	0.304150	0.294000	0.316750	0.350000	0.294000	0.316750	0.350000
A16	0.470400	0.554400	0.608300	0.588000	0.633500	0.700000	0.588000	0.633500	0.700000

[1] Computer dispersion configuration.
[2] Automation level.
[3] Units = millions of dollars, ten-year costs.

TABLE 13

CONTROL AND DISPLAY TOTAL TEN-YEAR COSTS AS A FUNCTION OF SOPHISTICATION AND MISSION

	CONTROLS		
	LOGISTICS: $C_{LL}(LP)$	RECONNAISSANCE: $C_{RL}(LP)$	WEAPONS: $C_{WL}(LP)$
L1[1]	0.0039[2]	0.00465	0.004725
L2	0.004125	0.004875	0.00495
L3	0.0038625	0.0046125	0.0046875
L4	0.0045	0.00525	0.005325
L5	0.004725	0.005475	0.00555
L6	0.004725	0.00585	0.00555
L7	0.004725	0.00585	0.0059625

DISPLAYS					
$C_D(DM)$	0.164	0.220	0.268	0.280	0.333
DM[3]	D1	D2	D3	D4	D5

[1]Control levels.
[2]Units = millions of dollars, ten-year costs.
[3]Display levels.

the data in Table 14. These results are shown in Figures 6 through 10. In each graph, three curves are drawn. The lowest curves are for all study variables (except the independent variable in the graph) held constant at their lowest values. The highest curves occur when the study variables are held constant at their highest values. All of the possible 5,040 cost-effectiveness values explained previously must lie on or between these extreme curves.

At the right of each curve is a percentage number. This represents the percentage by which the highest point in the curve exceeds the lowest point. Thus, this number represents the maximum percentage cost-effectiveness improvement possible over the range of values of the independent variable. All of these numbers, three for each graph, are plotted in Figure 11.

The sensitivity results for the three composite parameters, α, β, and γ (defined in Table 10) are shown in Figures 12, 13, and 14. The expected values of α, β, and γ are shown by a dashed line and are the operating point values at which the main results were computed.

As shown in Figure 12, the cost-effectiveness figures of merit for the logistics mission are not affected by values of γ, the cumulative peak ratio of success probability, because the main equations imply that success probability for logistics is constant at 1.0--that is, if the aircraft survives the takeoff, flight, and landing, the mission is completely successful. Figures 13 and 14 show that the cost-effectiveness results are more sensitive to an increase in α than in β. This occurs because the operating point values (N_{eo} = 200 for enemy action and N_{co} = 1,000 for ordinary crashes) make changes in survivability against enemy action more influential. Figure 12, α and β have a more equal effect because for logistics, both N_{eo} = 1,000 and N_{co} = 1,000. Also, the lowest curve in each graph of Figures 12, 13, and 14 is flat because it is the base value.

One major conclusion can be drawn from these sensitivity graphs: there are no crossover points anywhere within the range of values used. A crossover point is a value of the independent variable where a system changes from being better than another to being poorer. The absence of any crossover points at all for the cost-effectiveness parameters would indicate that the choice of the best candidate is not dependent upon the accuracy of the cost and effectiveness data used.

This strong conclusion cannot be made here because not all possible values of α, β, and γ (as well as other parameters) have been studied. For instance, LCE (α) at β = 1.25 and γ = 1.5 was plotted, but not at β = 100 and γ = 1.00 which would surely add crossover points because of the increasing costs for more sophisticated equipment. Maximum cost increases were from 6 percent to 11 percent, while maximum effectiveness increases (combined α, β, and γ) were from 35 percent to 80 percent. Thus, the sophisticated candidates would become not cost-effective only if the improved effectiveness were estimated 600 percent to 700 percent too high.

TABLE 14

SIGNIFICANCE OF COST-EFFECTIVENESS CRITERIA

SELECTION CRITERIA	ECONOMICAL MISSION ACCOMPLISHMENT	MAXIMUM CREW UNBURDENING
AUTOMATION CHOICE	A15	A16
COST	LOGISTICS 7.4%	LOGISTICS 0%
EFFECTIVENESS	RECONNAISSANCE 16%	RECONNAISSANCE 0%
ADVANTAGE	WEAPONS 16%	WEAPONS 0%
	AVERAGE 13.1%	AVERAGE 0%
SAVINGS AT EQUAL MILITARY CAPABILITY	$520 MILLION/ 500 AC/10 YEARS	0$
INCREASED MISSION CAPABILITY AT EQUAL COSTS	LOGISTICS 7.4% TONNAGE	LOGISTICS 0%
	RECONNAISSANCE 16% TARGETS	RECONNAISSANCE 0%
	WEAPONS 16% KILLS	WEAPONS 0%
	AVERAGE 13.1% PERFORMANCE	AVERAGE 0%

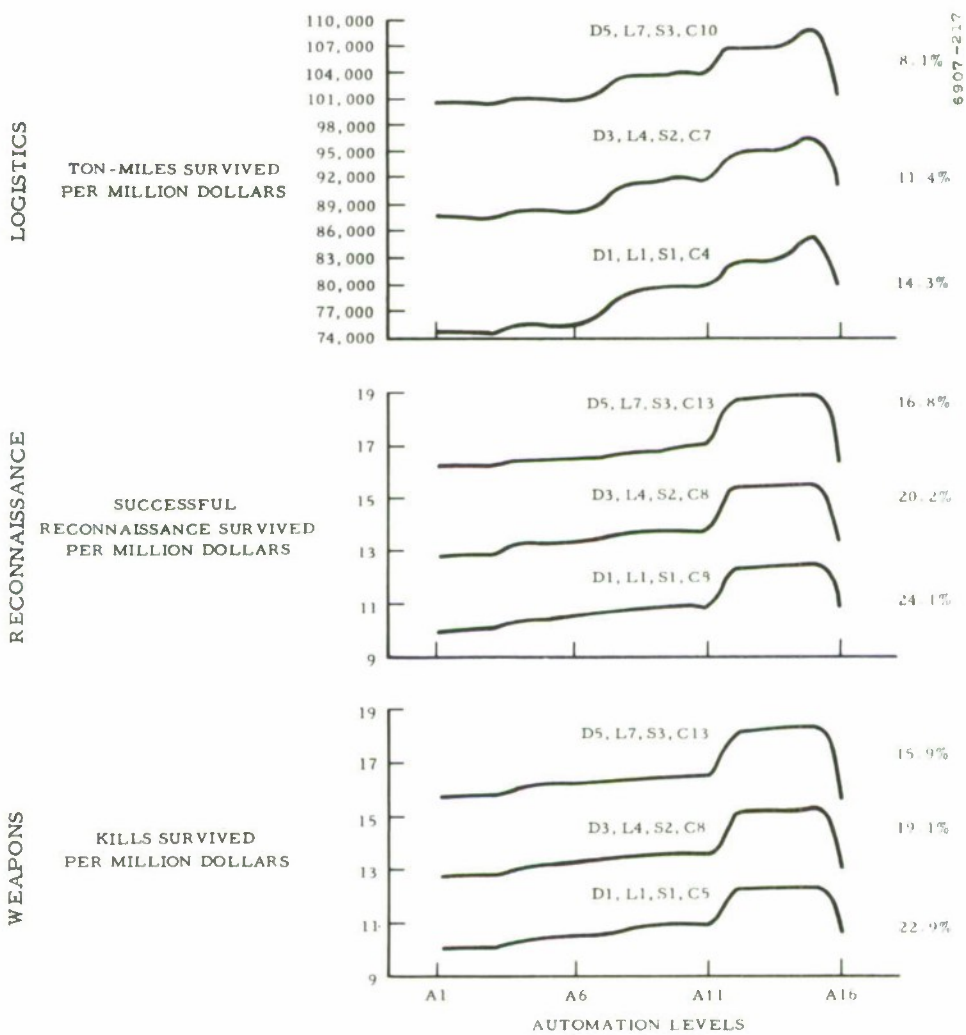

Figure 6. Automation effects on cost-effectiveness.

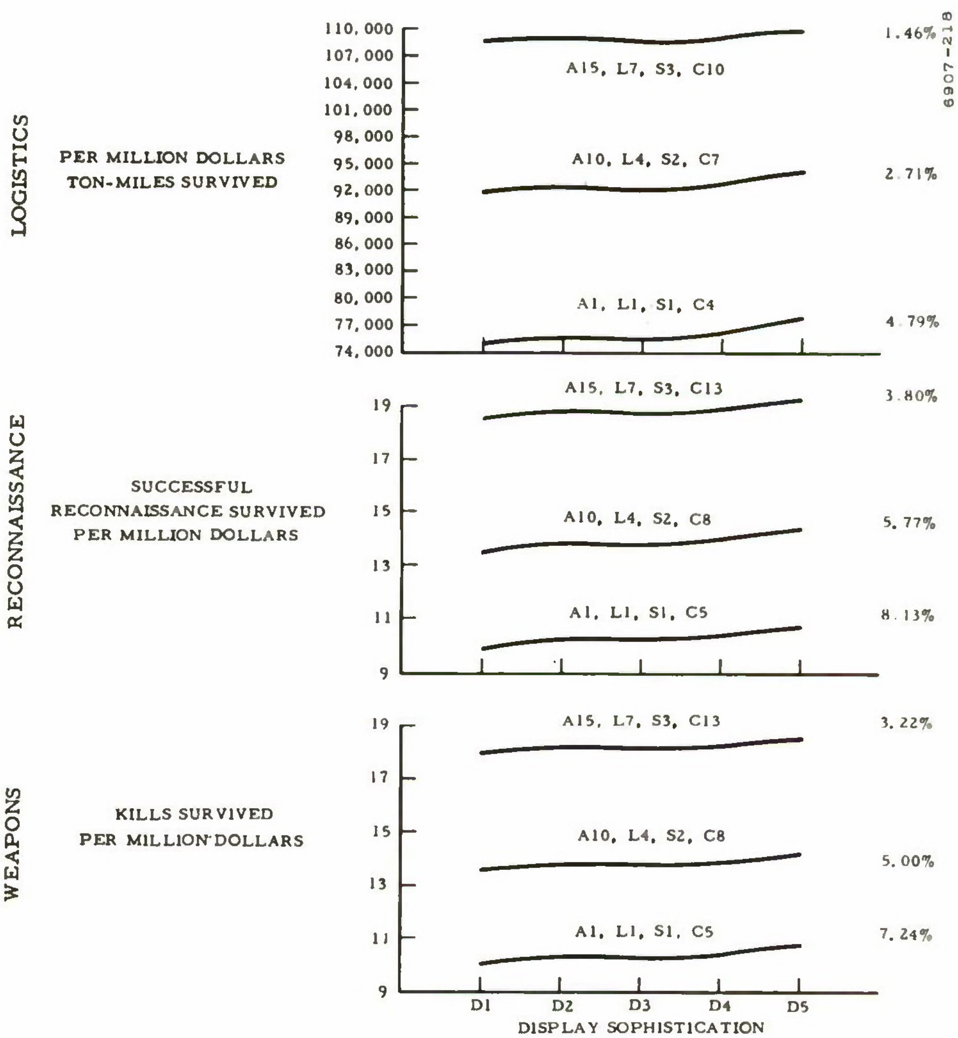

Figure 7. Display effects on cost effectiveness.

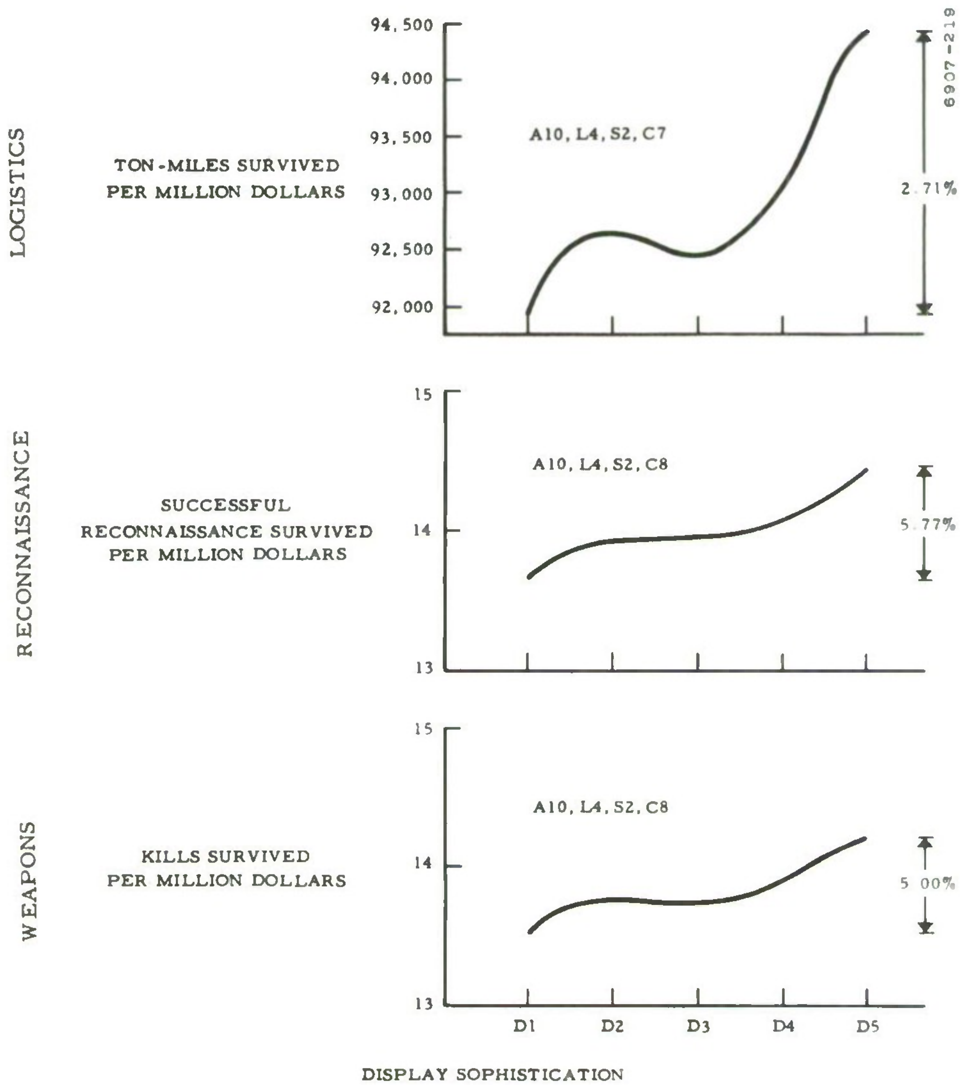

Figure 8. Display effects on cost-effectiveness.

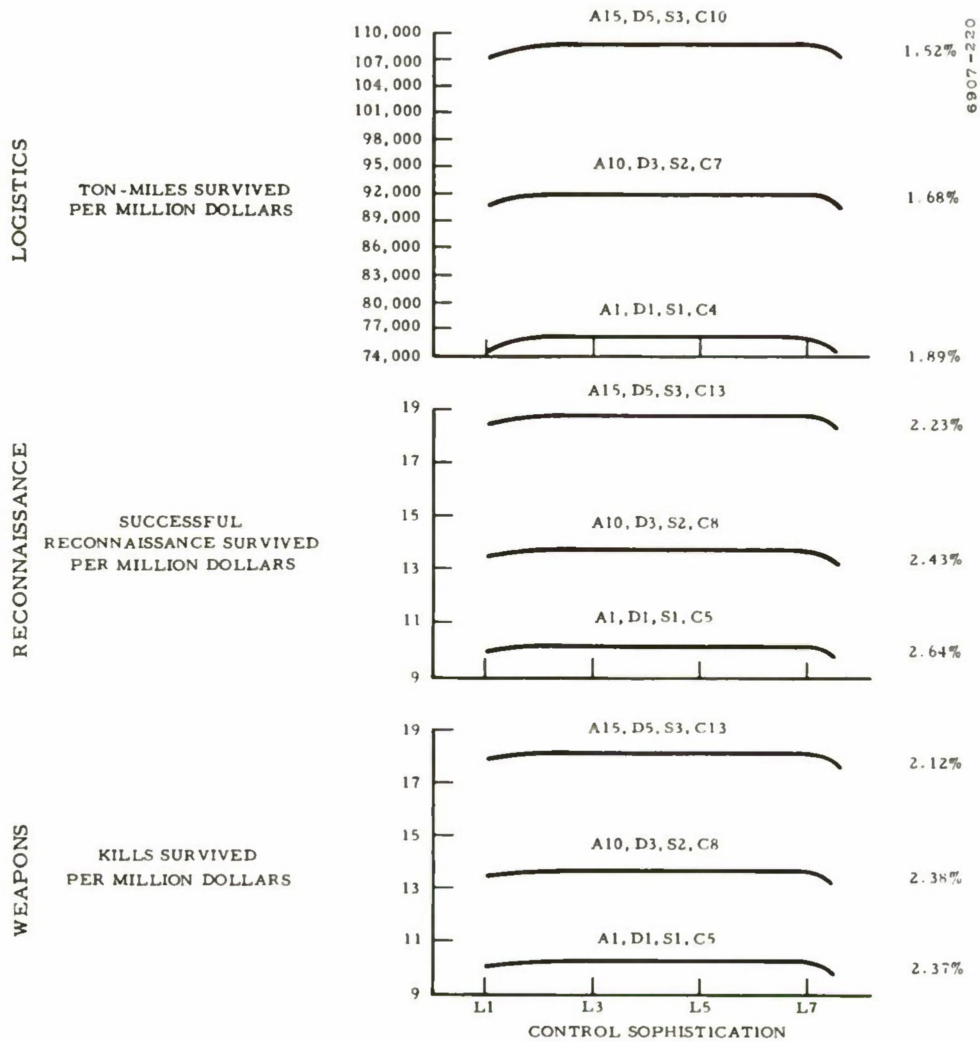

Figure 9. Control effects on cost-effectiveness.

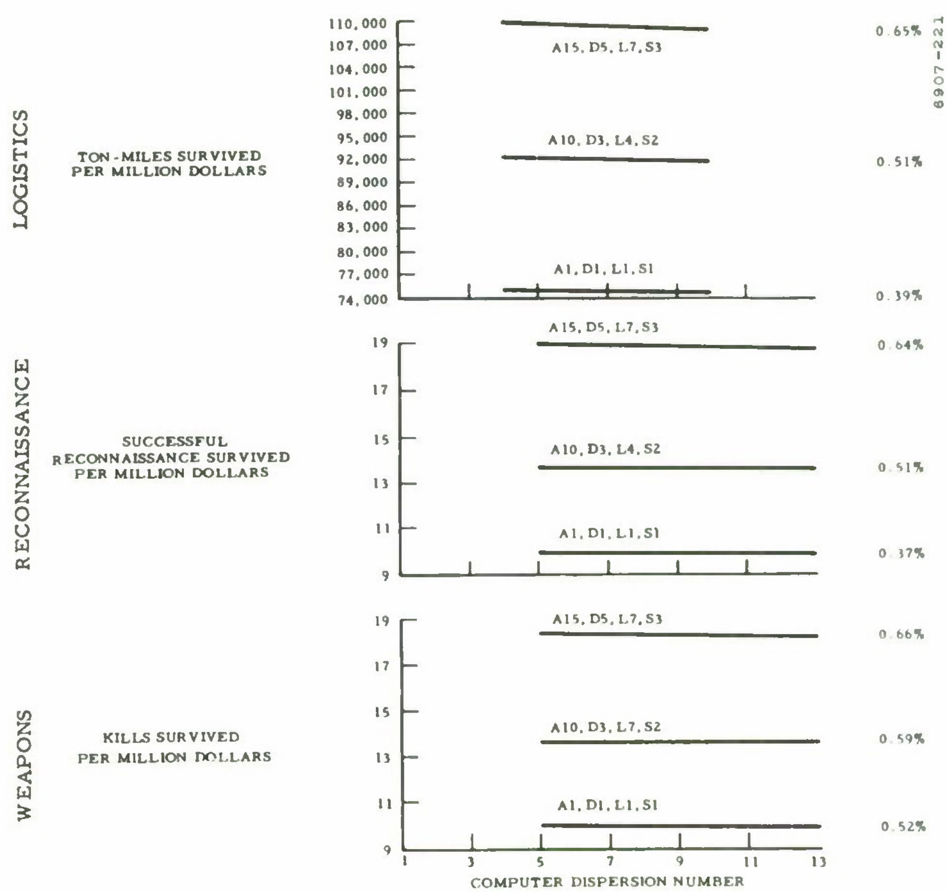

Figure 10. Computer dispersion effect on cost-effectiveness.

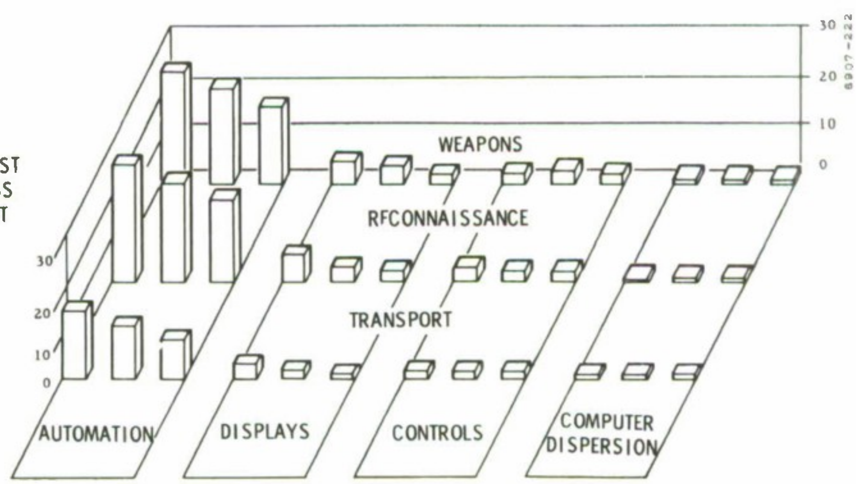

Figure 11. Areas of cost-effectiveness improvement.

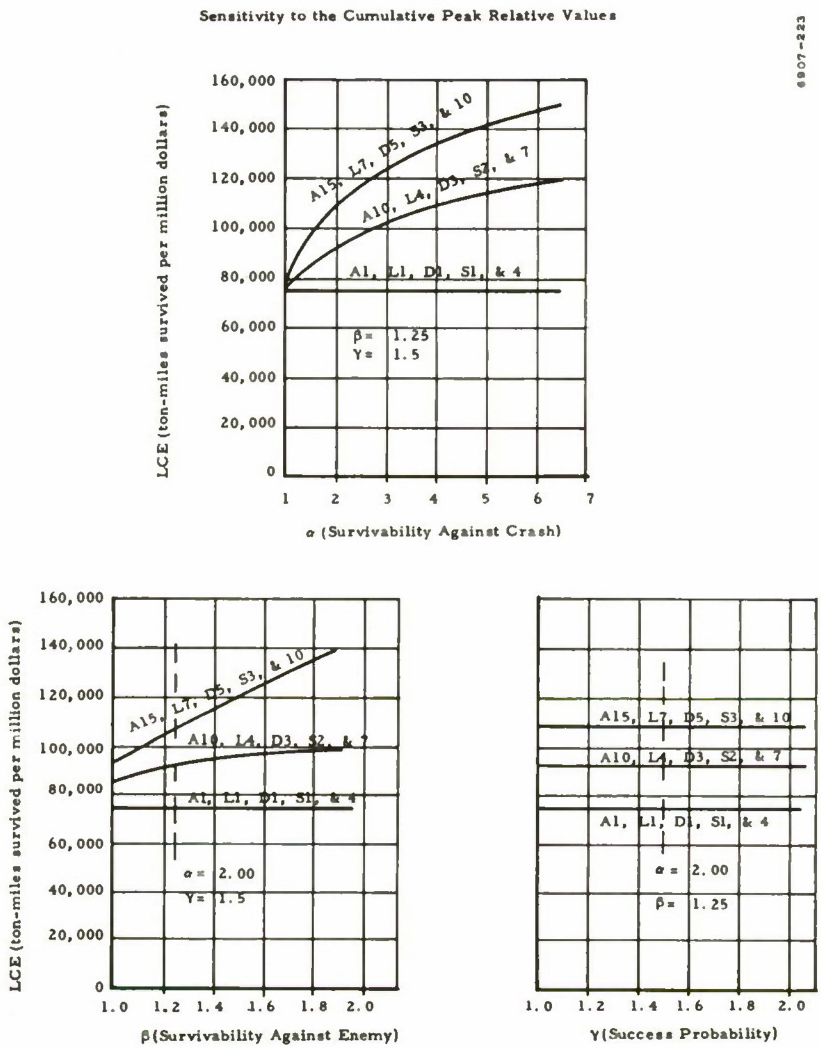

Figure 12. Logistics cost-effectiveness.

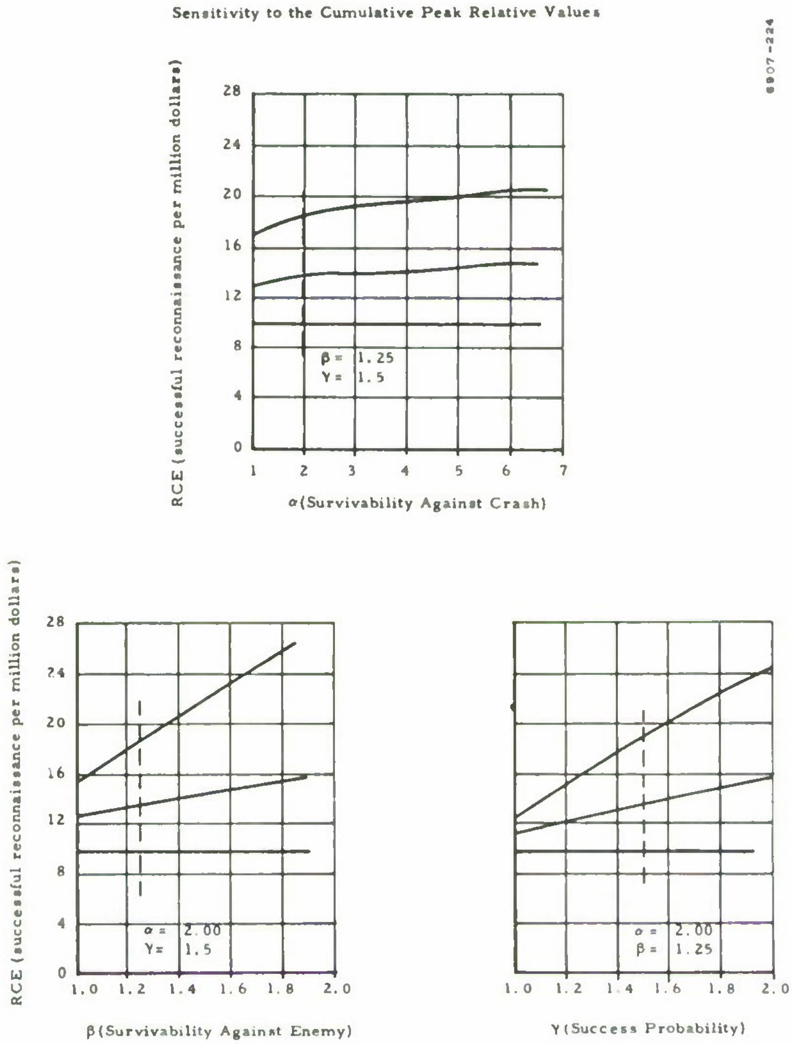

Figure 13. Reconnaissance cost-effectiveness.

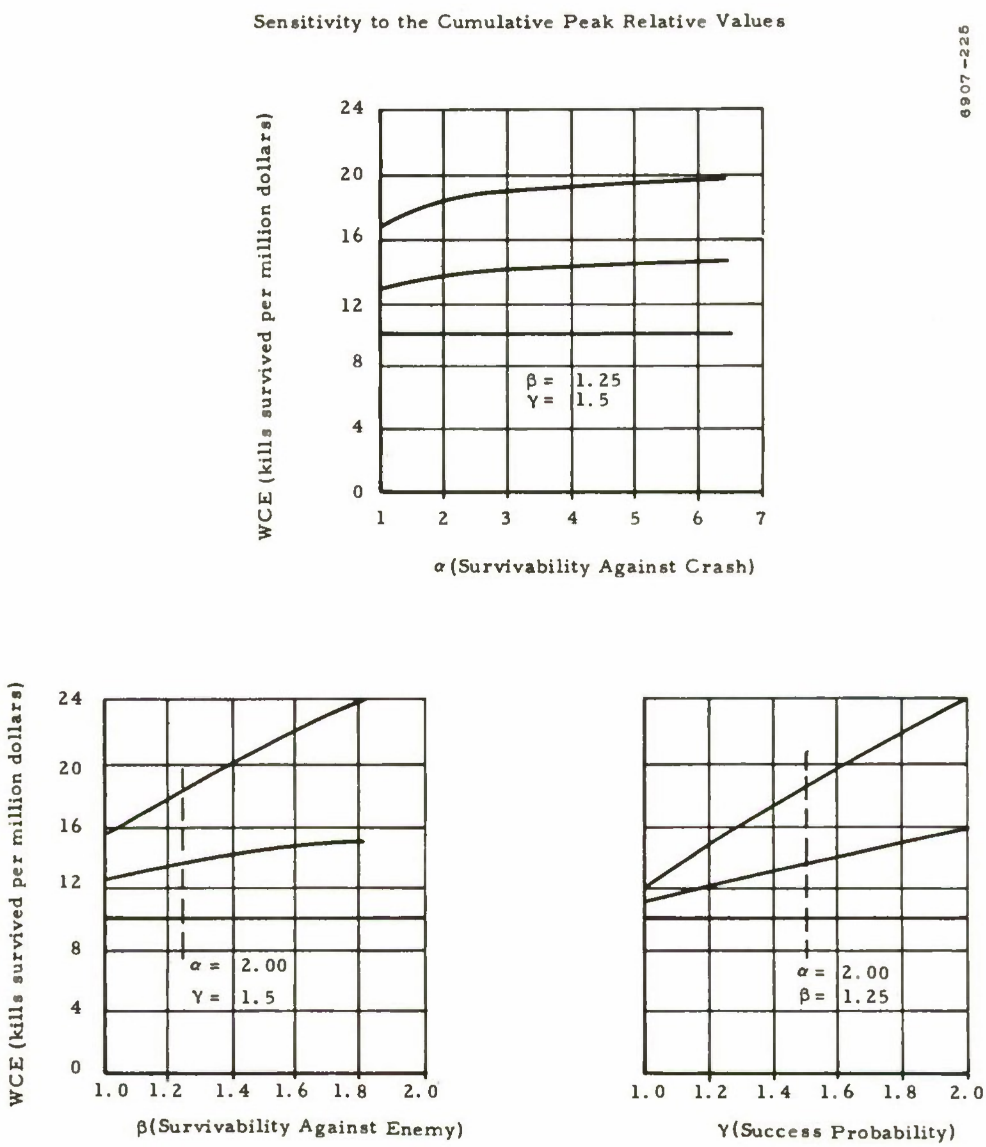

Figure 14. Weapons cost-effectiveness.

Another reason that such a strong statement cannot be made is that the relative accuracy of each candidate is not certain, although those that made the relative estimates felt strongly that they were reasonably correct.

Thus, the cost-effectiveness results are stable if it is assumed that the variable's levels were ordered reasonably correctly (Table 11) and that the effectiveness increases were not overestimated by more than 600 percent (Table 10). It might be added for completeness that the cost increases, also, must not have been underestimated by 600 percent or a combined effectiveness and cost error totaling 600 must not have occurred. All major errors are fully expected in the effectiveness data area, not in cost, because the extrapolations from direct experimental data and direct experience were greater in the effectiveness area.

Within the time and budget of the ICRP, various refinements were made where the data estimations of Tables 10 and 11 were carefully reconsidered. All results discussed represent only the final iteration.

IDENTIFYING THE COST-EFFECTIVENESS STRATEGIES

Several conclusions will be presented, tempered by the results stability and the expected effectiveness data weaknesses. The conclusions are dependent, to some extent, on the three missions. In general, Figure 6 shows that the most cost-effective level of automation is A15, for all three missions, and the extremes of more automation (A16) or less (A14), A13, etc.) should be avoided. Actually, levels A12, A13, A14, and A15 for reconnaissance and weapons are about equally economical because they differ by less than 0.5 percent. But A15 for logistics is 2.3 percent more economical than A14.

Not every automation level, as it was added step by step from A1 to A16, was cost-effective. This can be seen from a detailed study of candidates 1 through 48. For instance, the automation of energy management to 100 percent in A11 drops the figures of merit (in seven out of nine cases) a fraction of a percent.

In general, Figures 7 and 8 show that the most cost-effective display level is D5 and that less sophisticated displays (D4, D3, etc.) should be avoided because they are not economical in promoting mission performance. Again, not every step of display sophistication was cost-effective. The addition of a second head-up display in D3 drops the cost-effectiveness in seven out of nine cases.

Control sophistication generally increases the cost-effectiveness values about two percent as is shown in Figure 9. The most economical level in every case is L7, but L6 is close behind.

Physical dispersion of computer modules is not economical by about 1/2 percent as shown in Figure 10. Thus, the most cost-effective configurations are the more central-type computer complexes: C4 for logistics and C5 for reconnaissance and weapons.

A candidate can be selected having the best levels of automation (A15), displays (D5), controls (L7), and computer dispersion (C4 or C5). This is the aircraft system candidate number 100 which avoids the most uneconomical extremes in the variables.

SIGNIFICANCE OF A COST-EFFECTIVENESS BENEFIT

If a cost-effectiveness criterion had not been used in the ICRP, some other criterion would have been tried such as "maximum unburdening of the crew." With this peculiar selection criterion, the automation level A16 would have been chosen--clearly because more functions are automated, yielding the desired crew unburdening. Meanwhile, according to the cost-effectiveness criterion, A15 is selected. The A15 aircraft systems have an average cost-effectiveness advantage of 13.1 percent above the A16 systems. Thus, when 500 aircraft are deployed for the logistics, reconnaissance, and weapon missions for ten years, the 13.1 percent benefit means that 520 million dollars could be saved by purchasing the A15 systems instead of the A16 systems. In either case the identical military capability is procured.

The 13.1 percent advantage can be taken solely in military capability rather than in a cost savings. At constant cost, 13.1 percent more military capability would be procured with the A15 system. This means 13.1 percent more tons carried for logistics and 13.1 percent more targets acquired or destroyed for reconnaissance or weapons. Table 14 summarizes the advantages of using a cost-effectiveness selection criterion rather than a criterion based on maximum crew unburdening. By using the cost-effectiveness study, uneconomical extremes in unburdening (automation), displays, controls, and computer dispersion were avoided.

OTHER STUDIES

A similar study to the one just described was conducted for the STAAS (5-9) program under contract to the Avionics Laboratory, USAECOM (Bernberg et al., 1968). The primary goals of the study were to evaluate (a) side-by-side versus tandem positions of the two operators in a conceptual aircraft envelope, and (b) the degree of sophistication and

configuration of displays and controls within either the tandem or side-by-side configuration. In this study, five candidates each were constructed for the side-by-side and tandem configurations. The aircraft was to have a reconnaissance mission, so crew workload coupled with display sophistication was germane to mission success. Effectivity variables and cost variables concentrated in the display-control variations. Again, professional judges were used to provide effectivity judgments against the selected display-control configurations. The results were rather clear and consistent. The study illustrated the value of the methodology and pointed the way for further development and refinement.

One other study, recently completed, called AIMAIS (10-12) under contract to JANAIR-ONR, was conducted to develop more extensive performance and reliability inputs as well as quantitative human factors data to evaluate differences among several cockpit-display configurations (Clark et al., 1971). However, this program was too ambitious for the scope of its contract and was only able to approach this problem and to identify some software mechanizations to help the evaluation process.

RESEARCH REQUIREMENTS

Research is needed in the following areas:

- How to provide consistent and valid professional judgments as inputs to the process.
- How to refine the effectivity inputs to provide meaningful data and to encompass mission requirements.
- What kind of human performance data are required to help evaluate such a process?
- What other cost-effectiveness approaches are there to evaluate crew-system design?
- To what degree can we develop software programs to enable us to rapidly accomplish the process without "abstracting down" to a manually tractable process--as we have accomplished in our time-based load analysis.

I presume readers have other questions in mind. We should heavily investigate the area that these three studies have pioneered. It is a useful and practical area of concern.

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Clark, R. R. et al. *Performance/reliability study of an advanced integrated modular aircraft instrumentation system, final report.* Tech. Rep. N00014-69-C-0424, NR213-071, Litton Guidance and Control Systems Division, Woodland Hills, CA, December 1971.

DISCUSSION ABSTRACT

• *Mr. Hollander, Hollander Associates:* Dr. Bernberg, what was the cost in either dollars or man months of the three items--data collection, model design, and evaluation? How did it break down approximately?

• *Dr. Bernberg, Litton Systems, Inc.:* I think the whole study was only a 6,000 man-hour study, and I would say that the cost-effectiveness portion of it probably was 15 percent, or 20 percent at the most.

• *Mr. Hollander, Hollander Associates:* And of that 20 percent, how did it break out between these three elements--data collection, model design, and then the actual evaluation work?

• *Dr. Bernberg, Litton Systems, Inc.:* I would say about equally.

• *Mr. Hollander, Hollander Associates:* First of all, I am a little concerned that the state of the art in cost-effectiveness evaluation that has been presented here is based on work that was done in 1966. This was probably

excellent work in 1966, but it is now 1972. I hope that in the workshop this afternoon we can get into some of the aspects that ought to be looked at in 1972.

You mentioned several times that the human factor inputs were emphasized, but when you come right down to it only two aspects of human factors were even looked at in this study. One was that the crews were arbitrarily divided into three sectors--average, above average, and below average--in about equal thirds. The other human element was a judged improvement factor. I believe today, six years later, we should look at more specific factors such as the physical, psychophysical, mental, and personnel training factors and in terms of absolute numbers such as those discussed yesterday by Dr. Meister. The models discussed today were almost simplistic by current standards. So, I believe that we can do a great deal more if we investigate additional factors. I recognize this study has very little time in it, but could you offer somewhat more advanced methodology today? Particularly, when we come to your selection? I think it is important to remember that whenever we choose to neglect a factor we must be able to prove its effect is negligible. That proof need not necessarily be analytical, but at least it must be a determination, a finding of fact or of formally saying, "Yes this factor is negligible," not just a convenient sweeping under the carpet by saying, "I can't do a thousand, therefore I'll sweep 997 under the carpet and concentrate on three."

• *Dr. Bernberg, Litton Systems, Inc.:* We concentrated on 102.

• *Mr. Hollander, Hollander Associates:* I am sorry, not 102 combinations, about five factors. Fundamentally there are about three classes of cost-effectiveness studies: the specific system oriented study, the standard simulation, and the analytical study. The studies themselves can be evaluated on the basis of the cost of data collection, the cost of model design, and the cost of evaluation. Apparently, as I understood Dr. Meister yesterday, if one is willing to spend enough money to develop really good analytical models, it is best to spend the maximum amount of money on the evaluation model. This model is reusable, so that the cost of evaluation eventually becomes very low--provided you make that initial investment. Some of the other studies are more quick and dirty in that results are oriented so that you can use them tomorrow rather than two years from now when the model has finally been developed. Fundamentally what I am saying is that cost-effectiveness methods have advanced considerably in the last six years. There are three classes, and I think one of the key items we have to concentrate on is how much preliminary work can be funded or can be done so that good models are available to evaluate a specific project.

• *Dr. Jones, McDonnell-Douglas Corp.:* I think in the modeling, one of the areas I did not hear emphasized was manpower costs. Right now, something like 60 percent of the DoD budget is devoted to manpower. Hardware is a smaller portion of the budget. And the manpower problem will become even more severe with the zero draft. Despite this, your analyses only included the human factor as it affected hardware costs. Manpower costs for one life of one system would seem to be an overwhelming variable which must be included in such analyses. Let me give you an example. Early in the design of a system we examined the impact of one crewman versus two. We could design a system that could be operated equally well by one or two crewmen. The addition of the second did not add significantly to equipment costs, but it did add significantly to life-cycle manpower costs--nearly two-thirds of a billion over five years. We are also developing the ability to predict manpower costs from subsystem design features. For example, under a USAF sponsored study we have obtained multiple R's in the 90's between the electronic equipment characteristics and maintenance training difficulty and costs. My point is that crew aspects tend to affect life-cycle costs much more than immediate hardware costs. This factor related to salaries, training, accidents, etc., should be included in your cost-effectiveness studies and should be recognized by management as an important element to consider in the procurement of hardware.

WORKSHOP PROCEEDINGS

CHAIRMAN: DR. RAYMOND E. BERNBERG, LITTON SYSTEMS, INC.

NOTE: THERE IS NO INFORMATION AVAILABLE ON THIS WORKSHOP EXCEPT THE FOLLOWING SUMMARY.

WORKSHOP SUMMARY

Dr. Bernberg, Litton Systems, Inc.: Cost effectiveness, I guess, means a lot of different things to a lot of people, even though it really is something quite specific. At our workshop I would have liked to have discussed specific questions and possible answers such as those I tried to present at the end of my paper so that we could develop methodology or explore some ideas about them. Rather than that, and it satisfied the needs of the people there, we posed lots of questions about the nature of cost effectiveness itself: where it belongs; what it is; how do we use it; etc.

Some of the questions we explored in our general discussion of cost effectiveness were the following.

- Can we use cost effectiveness as an incentive for improved design?
- Can we use cost effectiveness as a communications tool?
- Should cost effectiveness be applied to single items--absolutely or relatively?
- Is cost effectiveness currently causing overautomation of systems?
- What data are needed to improve cost effectiveness?
- How much emphasis should be placed on cost effectiveness in overall systems decision making?

Although, as I have said, we did not reach any specific conclusions in these areas, the workshop consensus was that further research is needed to develop methodology for strenghtening cost effectiveness as an analytical tool in the crew systems design process.

OPEN FORUM

SECTION X

• *CDR Hammack, Office of Naval Research:* This period has been set aside to give participants the opportunity to voice their views and to address questions to our speakers, sponsors, and other participants. Please feel free to comment on any issue that has emerged during the conference and to present new issues you feel have been overlooked. We would also appreciate hearing your opinions about the suitability of the conference objectives and the extent to which the conference objectives have been met. The floor is now open for questions and comments.

• *Mr. Fisher, Lockheed Aircraft Company:* I would like to address this question to the total group assembled here. It is addressed to industry, to our DoD brethren, to our government agencies and to NASA. I think we have done very well at meeting the conference objectives at the subsystems level. However, certain elements that are important in crew systems design have not been discussed. I think we have overlooked test and evaluation, maintainability, and personnel selection and training. Although often alluded to, these topics have not been discussed in sufficient depth at this conference. Another point of criticism I address to all of us. We have the mature managers, the senior people of our organizations, the senior service officers present at this meeting but we have not brought any junior people. That concerns me because we are supposed to be trying to work out problems for 1975 to 1980. If we are to leave a legacy, to devote ourselves to problems, to try to get directions in the workshops, we must bring our junior people to these types of meetings and motivate them. And why did we not bring some of the SPO project men from the Air Force, some of the Navy commanders, some of the admirals, and some of the Air Force generals who are not now sensitive to our problems and let them get a feel for them. We cannot limit ourselves to problems at the subsystem level; we must also seek ways to communicate upward and get the top people to begin communicating downward.

• *CAPT Rasinski, USAF Air Training Command:* I would like to support Mr. Fisher's comments regarding the need for a concerted effort to interest top-level managers in the potential of our wares.

• *Mr. Mueller, Army Aviation Systems Command:* The sessions and overview papers have alluded to a lack of cooperation or sympathy from project managers. Being in a project office, I would like to state that project managers are becoming more and more aware of the need for human engineering in the system crew space. And since some of you have been unable to communicate with us, we are here trying to understand you. The project manager is probably more aware of the need for crew station system and display requirements than you give him credit for. However, when he asks for help he gets very little usable information. I have been told by some gathered here that the reason is because I have not gone to the right person. I am here today and I find no answers are available or else we need more data, time, better definition of the problem, etc. The point is the project managers are ready for answers. We do not need more questions.

• *CDR Connery, Office of Chief of Naval Operations:* I have a comment for consideration by the panel--particularly for Dr. Bernberg--on cost effectiveness. It was my impression in hearing your paper that the approach was strictly oriented toward dollar cost and dollars saved. I did not hear anything mentioned about lives, other than in terms of survival, and even then, systems survival seemed to be emphasized. This implies that the human is expendable, which does not inspire confidence--particularly for the users of new systems. New systems should, I feel, make the prospective operator supremely confident that he will accomplish his mission and survive. Without this, no system is cost effective.

• *Dr. Bernberg, Litton Systems, Inc.:* I think what you said is very true. In assessing the life-cycle cost of the aircraft and the avionic suit that made it up, there is no way of assessing in dollars the number of people who may have died and been injured. It is an issue that we should be thinking of, but quite honestly, I have not seen any development in the last 15 years that has come to grips with this problem. Perhaps the difficulty of assessing the dollar costs of human survival accounts for this.

• *Mr. Moreland, Army Aviation Systems Command:* I just want to let Dr. Bernberg know that the Aeromedical Research Laboratory at Ft. Rucker in conjunction with USABAR has studied the cost of human lives and I think they have published their findings. This study considered: insurance costs, costs of settlements, cost of training, and other costs associated with the loss of Army personnel.

• *Dr. Teel, California State University:* Both yesterday and this morning, I heard many comments that reflect a defeatist attitude--as though people in this field have not really achieved very much. I also heard comments about the extreme difficulty in making any real progress. Although I have admittedly been three years out of this business, my experience was that the program managers were not impossible people, the pilots were cooperative, and we were able to make some rather significant steps forward. I wish the speakers had made some positive points, rather than just going over all of the old problems. Many of the speakers took me back 15 years, as if

nothing new had been accomplished. I just wonder whether the situation has really changed that much. Have program managers suddenly become tighter and design engineers more recalcitrant, or could it be that the human factors people are getting a little more chicken? I have also heard repeatedly the comment that "management doesn't understand us." Is that perhaps an excuse?

• *Mr. McIntyre, McDonnell-Douglas Corp.:* I think we would all agree on the ideal way we should work together to achieve optimum effectiveness in crew systems design. First, the mission of the plane to be designed would be specified. Then the requirements for human performance, lighting, life support, cost effectiveness, etc., would be identified. Accurate and usable human factors data would be related to necessary design considerations and we would then convince management to accept the design. Assuming all this work was performed correctly, we would produce a plane to perform its stated mission with perhaps 99 percent effectiveness. Unfortunately, out in the real world, aircraft often do not end up with the mission they were designed to do. In addition, new developments constantly appear, requiring crew systems modifications. Now this leads to my major point. In designing crew systems we must allow for growth potential, we must ensure flexibility. In the design process we should avoid increasing the pilot's workload just because certain new jobs can be done. We should avoid filling up the cockpit with unnecessary switches and buttons just because the space is available. And we must try to take into account anthropometric data from other countries that are likely to buy our aircraft. This is the economical way--we cannot always discard a plane because it cannot accommodate a new device or accomplish a different mission, and we cannot change the pilots themselves. So I would like to stress that flexibility and allowance for growth potential are essential considerations in crew systems design.

• *Dr. Jones, McDonnell-Douglas Corp.:* I would like to respond to Kenneth Teel, who commented from the floor that he did not think there have been changes since he left aerospace three years ago. The prototyping and fly-before-buy concepts have been introduced in the past four years. These concepts tend to deemphasize crew considerations and concentrate on hardware suitability. The implication is that crew and maintenance factors will not be considered until after the basic airframe is proven.

• *Mr. Romero, Consultant:* I would like to comment on LTCOL J. D. Boren's proposal to Dr. Godfrey regarding convening a military/industry working group to resolve the red versus white lighting issue. Red versus white lighting in aircrew stations has been almost continuously discussed for the past 30 years. The discussions are always the same, and each participant has some very valid reasons why he considers red or white better. This problem which can be confined to military aircraft for this discussion, can be resolved in one of two ways: by installing a red and a white lighting schedule in every military aircraft, or by evaluating scientifically what level of dark adaptation can be maintained when white lighting is used for instruments and control indicators.

Obviously, the first is not a good approach because it increases complexity, weight, maintenance, and cost. In considering the second approach, the important question that arises is: which is more important at night--reading your instruments or seeing objects outside the aircraft? For a military aircraft both are obviously important. The answer, I believe, must come from aeromedical personnel specializing in the physiology of the eye. We must know what happens to our visual acuity when the level of illumination causes the change from cone to rod vision.

We should also pay more attention to the problem of reflections in the windshields and other transparent enclosures. It is an engineering function to develop suitable baffles to inhibit glare and reflections, regardless of the color of the light or its degree of intensity.

I believe the illumination color issue and the glare problem can be solved with intelligent consideration of what is needed within the existing development and procurement agencies in our government. A group of dedicated and knowledgeable individuals reporting to an office--e.g., the Department of Defense, where recommendations would be reviewed and considered, could achieve the solution. To operate at a lower level, however, would be a waste of time and talent.

• *Mr. Amos, Grumman Aerospace Corp.:* The problem of software is real. However, the hardware problems are by no means solved. For instance, CRT brightness, contrast, phosphor color and persistance, resolution, reliability, and size still pose problems. The HUD has many similar problems. I do not believe that display standardization is practical because the display should be optimized for each application. It should never limit the sensor capability.

• *Mr. Kopchick, USAF Avionics Laboratory:* The crew system design problems were never addressed at this symposium. The wide diversity of expertise here can only find a level of commonality at the system, not the subsystem, level. Emphasis should have been placed on such things as: the crew station interface with its environment; the

interrelationships between the functional areas in crew stations; the types of approaches needed to help solve the system problem; and the commonality that exists among different classes of crew stations. My recommendation is that in order for this large group to make any progress, we must communicate at a system level.

• *Mr. Naurath, Naval Missile Center:* I would like to address a question to Mr. Romero. Examples of stages in the crew station development cycle include: establishment of requirements, evaluation of proposals, prototype controls and displays, fabrication of equipment, test and evaluation, and operational use. What human factors techniques can be used most effectively to incorporate advocated changes at each stage? Can we define who is responsible for each stage and what their functions and authorities are? Can we as a discipline set up administrative procedures to provide inputs at each stage?

• *Mr. Romero, Consultant:* The various stages of system development are very much in accord with the example you gave in your question. Considering the total crew system design process, the various stages of design and development are much the same as they were in the 1920's. The major difference today is the great number of people involved, most of whom engage in some form of semi-technical paperwork as opposed to pure design. This has tended to complicate rather than simplify the design process. The greatest underlying impediment to the total process is the presence of so many persons who can say "no" and so few who can say "yes."

With reference to your question about techniques that can be used most effectively at each stage to incorporate advocated changes, I feel that until top-level engineering management recognizes the behavioral scientist as a design specialist, no human factors techniques will guarantee the effective incorporation of advocated changes. For many years, the problem behavioral scientists are now encountering was experienced by the mechanical, structural, and aerodynamics specialists. Difficulties and misunderstandings were overcome through cross education that brought forth an understanding and appreciation of each discipline's problems and approaches that could be taken for the best solution. Great success was achieved through in-house lectures by design specialists, members of industry speaking before classes in the engineering universities, and design conferences in plant for the solution of inter-discipline problems that arose not only in the preliminary stage of design but throughout the production life.

In answer to your question about whether we can define who is responsible for each stage and what their functions and authorities are, I must state that this is the prerogative of top management.

And regarding your question about whether we can, as a discipline, set up administrative procedures to provide inputs for each stage, the answer is "yes." Initiative to establish a method or procedure to enhance production reliability, schedules, and cost reduction will be regarded favorably by management at all levels. The employee suggestion program in many leading industrial firms is indicative of management sensitivity to such initiative and resourcefulness. However, to ensure success of such initiative, the proposal to establish such procedures should be submitted to management most prudently. If the proposal has merit it will be given every consideration.

• *Mr. Lewis, Defence Research Establishment:* Throughout the conference, there was an appeal for more quantitative data. I feel that much of the required data can be obtained from well executed field trials. Canadian experience shows that field trials provide valuable information about what is needed in operational settings. System degradations can be assessed in this way and dollar values readily assigned to them.

Further conferences of this type are needed, perhaps on a two-year basis. If additional meetings are held, I sincerely hope that they will be composed of roughly the same representative bodies and countries as were present here. However, I feel the overview component at the general assembly should be deemphasized.

I was most interested in the informed views of the two representatives of the Air Line Pilots Association and Colonel Madero. As pilots interested in research as well as the "gut" job of flying, their remarks were stimulating and most revealing.

• *Mr. Shirley, Lockheed Aircraft Company:* Many different problems have been described--lack of data in many areas, lack of money to develop the data, and lack of understanding of crew station importance by those who hold the purse strings. As someone said earlier, these are old problems and nothing has changed in 20 years. Nothing is going to change in the next 20 years either if all we do is talk about our problems and do not constructively sell crew station design to the industry, to the management, and to the services. Not much is accomplished by listing the holes in our data and saying sorry but we do not have enough money to cover all the bases.

If we developed criteria for evaluating the crew station in terms of system effectivity, safety, etc., and related all data to cost, this could work miracles for the crew

station design process. In the same way the structures man can say the wing spar has to be of a certain size or else limit the G loading and mission of the aircraft, we have to be able to say the cockpit has to be of a certain size or else limit the level of crewman effectivity and vehicle safety. Some time ago the Navy made a study relating cockpit size, the big man, and the accident rate. Why can't that sort of thing be greatly amplified and made a useful tool?

Tools must be developed that have as much stature and meaning as the structures and aerodynamic formulas in use today--tools that can be used and understood by program managers and the industry. When the returns on cockpit improvements can be quantified, you can then sell management and get the money to fill in the holes in our data bank.

• *Mr. Romero, Consultant:* I would like to respond to Mr. Shirley's comment. The intent of the conference was to promote the timely use of the best available technology in the development and evaluation of crew systems. The total objective was to demonstrate that improved crew performance as well as reduced costs can be achieved with the proper blend of management and technology. The overview papers were intended to set the stage for the workshop participants in an effort to bring forth procedures and techniques that individuals and organizations are using to develop more usable and efficient work areas required by aircrews. It was believed that open discussion would bring forth suggestions for the development of criteria for the evaluation of crew systems in terms of cost effectiveness. Although this was not achieved, considerable thought and discussion have been generated and it is believed this will result in better inter-disciplinary communication. This is a necessary first step if a method for generating and compiling criteria for meaningfully evaluating design and cost effectiveness of systems is to be achieved.

• *Mr. Smith, North American Rockwell:* I should like to offer one suggestion. The conference should solicit the active participation of the entire pilot community in its workshop sessions. All levels of experience should be represented, from the sophisticated professional pilot through the relatively inexperienced private pilot group. These are the people who will ultimately use or misuse the products of your efforts and, as such, represent an invaluable source of information for design consideration. These pilost must live with and operate your equipment long after the design is completed, and the designer has gone to bigger and better things.

The Air Force now requires, through AFR 80-14, that the using command be actively represented throughout all phases of the procurement of a new system, from design conception through deployment. The term "operational suitability" is now accepted as one of the more important criteria in the procurement cycle. I suggest that your organization give more consideration to this factor in your future meetings.

• *Mr. Smith, Texas Instruments, Inc.:* Standard panel sizes need to be developed. We can, of course, have more than one panel size, but whatever we have must be standardized. We already have some standards, such as ATR racks, but we need more.

• *LCOL Boren, USAF Aeronautical Systems Division:* Mr. Romero, I believe that most of us would agree that we fail to incorporate known human factors into our systems as they are developed, primarily because of hardware orientation. Do you think if a high level DoD office were to serve as a focal point for human factors matters that it would aid in incorporating human factors into the system? If so, how do we go about establishing an office that would provide such a needed top management contact?

• *Mr. Romero, Consultant:* I do not believe that a high level DoD office serving as a focal point for human factors matters would aid in incorporating human factors into the system. Human factors requirements will be successfully incorporated into the system only when human factors personnel and hardware design engineers develop mutual respect for each other as specialists and endeavor to appreciate their respective inherent problems.

• *Mr. Fadden, The Boeing Company:* Display technology has reached a point where extremely flexible devices are available for both research and operational use. The practical limits of computational power associated with airborne displays have expanded tremendously in the last few years. Very often the critical display question is not whether certain information can be displayed but should it be displayed? Simulation and flight testing can be effectively used to obtain physical measurements of pilot performance as a function of display content. However, as we have been told many times during this conference, pilot acceptance of new displays is not solely a result of demonstrated performance improvements. A question that should be addressed at this conference is: should new measurements be made to attempt to quantify and thus design for the "acceptability" factors or should the display designer concentrate on education and salesmanship once a display has been optimized for the performance factors?

• *Mr. Julian, General Electric Company:* I have a question for Mr. Romero. The controversy on vertical scale instruments versus round dial instruments has gone on for some

time, but never before has a pilot used both in the same aircraft. This, however, has been changed with the advent of the 747, the L-1011, and the DC-10 which may have either type, depending on airline preference. The airline test pilots have flown both. What are their reactions? They have added colors to distinguish between parameters, and adjustments to reduce the glare effect. Has this helped? Discrete digital displays and analog-only indications are now available. What is thought of each from the operational point of view?

• *Mr. Romero, Consultant:* It is difficult to state specifically the reactions of test pilots who have flown aircraft equipped with both the vertical reading and round dial instruments because I have talked with so few. However, I believe that if both types of instruments are equally reliable, the vertical reading instrument is easier to monitor.

Regarding color coding, the comments are generally favorable as are those regarding the reduction of glare.

I find it difficult to answer effectively your question about what is thought of digital displays from the operational point of view. I believe a survey of the operational population, military and civil, is required to do this. In order to achieve a true and unbiased assessment, great care in the preparation of a questionnaire is paramount.

• *Mr. deCallies, United Aircraft Company:* Back in about 1952, a program called ANIP, JANAIR's predecessor, was dealing with many of the same issues that have been discussed at this conference. ANIP was a program dedicated to improved aircraft performance within the man-machine context. Use of human factors and the concept of the man-machine system were the hallmarks of ANIP. Reports are still available from DDC covering practically every aspect of the program. It was apparent from the comments made at this conference that many individuals had little or no knowledge of the numerous research studies and reports generated by the ANIP and JANAIR programs. I find this surprising and distressing.

With respect to the conference itself, I feel that adequate communication among participants did not occur until the conference was nearly over. One could conclude that there was inadequate "warm-up" to get people to talk about the significant problems in crew station design. We need more of these conferences if we are ever going to be sufficiently self-analytical and objective about what we are doing and to communicate with representatives from disciplines different from our own.

• *CAPT Hawkins, KLM Royal Dutch Airlines:* I was delighted to hear your call for human factor education and appreciation among design engineers. Only the very large companies, however, can possibly afford fully qualified ergonomists, and no short course directly oriented toward aviation has been available for engineers in the rest of the industry.

The first effort to correct this notable deficiency has now gotten off the ground, with a two-week specialized course on "Human Factors in Transport Aircraft Operation" at the University of Technology, Loughborough, England. While this course will not turn out fully qualified ergonomists, it should make participants capable of recognizing human factors problems, able to solve the more straightforward problems, and aware of when more specialized assistance is needed.

• *Mr. Loose, Radio Corp. of America:* As a representative of those who are working in advanced technology, I would like to endorse wholeheartedly the remarks made by Dr. Geoffrey Hunt of the RAE. Hardware and software development must continue. Attempts at standardization must proceed cautiously because of the wide variation in mission requirements and the constantly advancing technology. It would appear that considerable work is needed in defining pilots' information requirements. How much information can they assimilate? How can it best be presented? What types of controls can they use most effectively in performing their missions? Those engaged in hardware and software development must seek answers to these questions.

• *Mr. Armstrong, Bunker-Ramo Corp.:* A process should be established whereby the cockpit designers and human engineers can honestly report the deficiencies in their design without destroying their "sales pitch" during the proposal cycle. These individuals should be rewarded for discussing and exposing design shortcomings and should be allowed to suggest methods to resolve the deficiency. This procedure would reduce the attempts to justify poor designs by unrealistic statistics aimed at "selling" the product.

• *LCOL Madero, USAF Instrument Flight Center:* I have a nagging impression from this conference that our present control/display/guidance problems are being overlooked in favor of future innovations and requirements. I strongly recommend that the present-day problems that pilots face be addressed and resolved before attempting to solve the problems of the future.

• *MAJ Madson, USAF Aerospace Medical Research Laboratory:* The overall crew system escape concept uses piecemeal life support equipment items, all of which have undesirable elements that compromise a crew member's efficiency. This concept is based upon the assumption that each aircraft must have its

own unique crew compartment with its various components--e.g., ejection seat and parachute. And providing and maintaining this multiplicity of separate components constitutes a major expenditure. Would it not be more economically feasible to amass the data and technology available to develop a standardized shirtsleeve crew compartment for all future developmental high performance aircraft? What real problems might be encountered in developing such an item?

Present technology has launched man to the moon in the comfort of contoured seats in a shirtsleeve environment. This has occurred during the same time period in which pilots were injured and/or killed due to high speed ejections, suffered serious back injury due to ejection forces, incurred head injury due to loss of helmets on ejection, and expressed constant dissatisfaction with the discomfort and inconvenience of personal equipment. Currently, ejection seats are being modified, new parachute concepts are being devised, and new helmets, masks, and other personal equipment are being developed in an effort to gain greater safety and comfort. We should employ our space age technology to develop a new escape and recovery concept and marry it to new airframes. We are losing ground trying to Rube Goldberg our present systems and concepts to keep pace with the increased performance of aircraft under development or on the drawing board.

• *Mr. Stephens, North American Rockwell:* Flying today's highly sophisticated aircraft with their increasingly complex systems has given the pilot an enormous workload. Performance is often degraded by the reduced time available to accomplish necessary tasks. Also, the console and instrument panel areas have become too cluttered for efficient use. More and more controls, displays, and indicators are installed in each new system. In addition, the advent of high-g, high acceleration aircraft will impose even more constraints on the crew member. Restraints and supine positioning of the crew member will greatly reduce his capability to perform manual tasks.

The number of controls, displays, and indicators must be reduced. Aircraft and avionics systems must be studied to determine methods for reducing the crew members' workload. With the expanding role of the aircraft and the need to monitor more and more systems, this reduction can be accomplished only by consolidating the controls and displays. Mr. Thomas Suvada's recommendation of multi-function display systems is an approach in the right direction. Crew station requirements need to be evaluated to determine which parameters must be displayed constantly and which can be consolidated into multi-function display systems. An airborne installation and evaluation of such a system must be performed to provide us with the information needed to allow advancement toward the goal of providing aircrew stations to keep pace with the advancement of aircraft technology through the 1980s.

As a representative of a military airframe manufacturer, I have found the crew system design conference very beneficial. I have found that many other people share my problems. Some approaches to solving these problems have been brought out in the controls and displays workshop.

• *Mr. Wulf, General Dynamics/Convair:* I wish to support the views of Messrs. Wolin and Suvada regarding the concept of an integrated cockpit approach and the use of multi-function displays. However, in my mind the multi-function displays are warranted only if cockpit congestion is relieved.

• *MAJ Odle, USAF Instrument Flight Center:* The overview presentations did little for the conference. I heard nothing new or revolutionary, in these presentations, and I think the material could have been better conveyed by mailing the papers to the participants before the conference.

The conference workshops would have been more productive if participants with common interests could have sat down in a group of 15 eyeball to eyeball and discussed their problems. The facilities for conducting the controls and displays workshop discussion were unbelievably bad. The physical layout just was not conducive to accomplishing work.

For a group of "human factors" experts, the presentations were extremely bad, no slides, slides upside down, and slides too small to see. And flashing the slides on and off the screen with side comments from the speaker did nothing to enhance the presentations.

It was rather obvious that most attendees were waiting for the others to tell them which way to go and what is needed.

I am amazed at the great number of control-display design engineers who do not even have a private pilot's license or have ever soloed an aircraft. I would think that manufacturing concerns would get a big dollar return by providing pilot training at least to private pilot level for their designers. I am not naive enough to think pilots have all the answers, but how can a man design something for use in an environment that is entirely foreign to him.

If there was one good thing resulting from the conference, it had to be that people talked to each other during the coffee breaks and this provided many persons with a better understanding of what other groups are doing in

their areas of interest. Its obvious that much money and effort is being expended in crew system design--witness the cost of getting the great number of people to the conference.

• *Mr. Wagner, Naval Weapons Center:* Nearly all of the speakers at this conference stressed the role of human factors in the overall crew system design process. When I came into this business about three years ago, designers and engineers considered human factors to be almost a swear word. But things have changed. Designers and engineers are now much more willing to communicate with human factors representatives. This change will surely cause human factors representatives to work harder to understand the engineer's problems.

• *Mr. Dalhamer, Honeywell, Inc.:* I get the feeling that the workshop attendees were sitting around waiting for Moses to descend from the mountain with a stone tablet listing the rules and design specifications that will solve the display problems forever. This is naive at best. I was surprised at the responses about "let's think of the cockpit as a total system." To think of this sweat box in any other manner is denying the problem. I also got the feeling that the aviation industry has refused to exchange innovative ideas about tools and methodologies.

Mr. Jack Wolin outlined a very ambitious program for this conference. I heard him say "give me tools, identify problems, etc." yet some of the remarks that he made reflected non-utilization of the tools available. For example, cross-track-rate as a potentially valuable piece of information for the pilot. This is true, but it was identified and incorporated into the PI-FAX panel in 1963-64 to assist in presenting important integrated information during the last few feet of altitude under IFR approaches. However, evaluation of the panel revealed that though the panel was located only four inches from the pilot's area of concentration during this portion of the flight profile, pilots did not or could not use the information because of its location. Why? The pilot's area of crosscheck is inversely proportional to the aircraft's altitude. That is, pilots begin to fixate on an area--and ultimately on a point--as the aircraft descends on final approach. These kinds of findings have been documented and pave the route that one can take in order to solve the total display system configuration.

Dr. Roscoe gave us some insight into his discovery of the "wheel"; secondary task measures as a sensitive tool for measuring pilot blunders and workload. Amen! I hear we have no measurement set to document pilot workload. No sales pitch intended, but Honeywell, Inc., has developed a technique for documenting pilot workload. However, Honeywell is as derelict as the rest of the industry for not making this tool known.

I sometimes wonder if the individuals specifying the control/display requirements realize that change to a component part of the display panel can influence the effectiveness of the overall control/display configuration. Once again, the systems approach is a must. We have only alluded to the Microwave Landing System which opens the door to a host of new problems. Auxiliary data requirements, curved path approaches, mode selection requirements, control/display augmentation to satisfy mission requirements for various types of aircraft, and monitor stations with an accurate and reliable monitoring system. If human factors engineers can make their inputs known in the developmental stage of Microwave Landing Systems, our discipline has come a long way toward achieving our goal.

I hope that industry and governmental agencies make a concerted effort to bridge the obvious communications gap. Let us develop an effective means to communicate our problems, desires, and capabilities without the underlying motive of greed.

• *Dr. Hunt, Royal Aircraft Establishment:* I do not think that very much has been achieved by either the general assembly or the workshops. The human factors establishment has exerted a great deal of effort to justify itself, but if I had been an observer completely unconnected with the industry, I would have felt that the case had not been made.

I feel that too much time was devoted to identifying problems, and too little devoted to identifying possible solutions. It would have been better if the problems had been identified before the meeting by the various committees, and discussion had been limited to these pre-defined areas. This procedure would have enabled the discussion to proceed toward problem solutions. The papers given in the workshop could then have been directly related to the problems and would have initiated the discussions. Unfortunately, the papers in the controls and displays workshop did not lead to discussions of any significance.

• *Mr. Moelker, National Aerospace Laboratory:* The conference sought to identify and evaluate the available technology and to foster better interdisciplinary communication in this field. The total objective was to demonstrate that improved crew performance as well as reduced costs can be achieved with the proper blend of management and technology. With the exception of Mr. Suvada's paper on CRTs, technology was scarcely mentioned at this conference. Furthermore, requirements were identified that called for new technology.

The requirements that were identified were described only vaguely. With respect to the communication problem, I feel that representatives from the technical disciplines have difficulty communicating with management and with the operational user. Communication among the technical disciplines seems to be pretty good.

• *CAPT Hawkins, KLM Royal Dutch Airlines:* The concept of bringing together those involved in all aspects of crew system design is excellent. To be really effective, however, we should have maintained a better balance between military and civil aviation at this conference. For instance, I do not know why more pilots from the world's leading airlines were not represented. Civil aviation has many operational problems that are common to those encountered in military aviation, so the exchange of problems and ideas would undoubtedly have been beneficial to both segments of aviation. Furthermore, since commercial airlines have little cabability to conducting research and development, this conference could have provided the mechanism for communicating problems to existing research organizations.

• *Mr. Fraser, Hughes Aircraft Company:* I feel that the scope of the conference was too large. It appeared that we were attempting to find definitive solutions to generalized problems. I feel the meetings would have been more productive if specific problems were outlined early in the session, and then small groups had been organized to attack each problem. I realize that this was attempted at a high level by breaking up into working groups, but some workshops were still too large to constitute an effective working group.

I work as a project manager on the F-14 rear cockpit. I deal with specific hardware problems every day such as how to enable the operator to control and display vast amounts of information in a small fighter cockpit; or how to make the information visible under all cockpit ambient conditions. I also have to evaluate state-of-the-art devices and technology to determine their applicability to the system.

I know that most of the other government agencies and contractors present are working on production aircraft or advanced designs. I think that it would be more fruitful to have a conference of this type run for a full week and to use at least the first three days having a good many of the participants give presentations with cockpit or mockup pictures showing what they are doing, what problems they have run into, how they solved these problems, or which problems they have been unable to solve. After the presentation phase it would be reasonable to extract specific problems for attack by the various committees. This approach would have the added advantage of providing an invaluable exchange of information about what is happening in our field at this time, where any duplication lies, who may have a solution to a problem, etc.

• *Mr. Randall, The Boeing Company:* The single most cogent comment I might make concerning the workshop proceedings is that most of the discussion was too specific. I would have been happy to have spent the entire time discussing just two areas of general interest: the establishment of a DoD agency charged with the primary responsibility for the human factors aspects in military procurement, and methods to obtain valid and representative pilot inputs to be used in formulating basic criteria governing cockpit designs.

• *Mr. Perutz, Hazeltine Corp.:* I was impressed with the variety of agencies and disciplines represented at this conference. It probably marks the first opportunity for these groups to communicate with one another. While this communication is highly desirable, I do not believe that the main objectives of this conference were met. That is, crew station shortcomings were not clearly identified, nor were methods for improving crew stations clearly defined. Perhaps, the sheer magnitude of the problem coupled with the large number of people present at the conference made it impossible to achieve our task. I believe that subcommittees should have been formed to deal with the problems over a time period longer than three days. These subcommittees should have been directed to attack one or more specific problems and a master committee should have been formed to integrate the conclusions of the various subcommittees.

• *Mr. Amos, Grumman Aerospace Corp.:* My reaction to this conference is very favorable. The fact that so many types of people were brought together and allowed to express their views has been most enlightening to me as a design engineer. The comments have made me more aware and appreciative of the problems at hand in the design and integration of an aircraft cockpit. I strongly recommend that more meetings of this type be arranged.

• *Mr. deCallies, United Aircraft Company:* I believe this type of conference is valuable. However, the large number of attendees made it difficult to meet the conference objectives. The displays and controls group was particularly unwieldy. The overview papers presented at the general assembly did not adequately define the state of the art. Apparently, greater selectivity and monitoring would have helped in developing better statements about "Where are we now?" with respect to crew station technology.

Conferences like this should be held almost yearly in order to better judge where

to go from here. Smaller groups of concerned experts sitting at the same table could probably generate a lot of appropriate technical information. The Air Line Pilots Association, All Weather Flying Committee, appreciates being invited to this conference and believes they have identified an operational requirement for HUD along with a research requirement for determining the required visual reference for safe low visibility approaches and landings.

• *Dr. Fenwick, Collins Radio Company:* I feel the workshops were improperly organized. It appears that the subjects are too complex to be addressed by a relatively unstructured assembly. A steering committee is needed to identify some central and timely issues, and the workshop moderator must lead the discussion with a rather firm hand. The give and take of discussion on specifics is more likely to produce useful outputs than a series of lengthy speeches by relatively few participants. We are all more or less aware of the broad generalities that have long divided our industry. We now need to minimize the number of subjects and explore them in some detail.

• *Mr. Thomas, Naval Air Test Center:* I think the conference was beneficial and informative from the standpoint of assessing one's own problems and frustrations within the context of the industry as a whole. The workshops, however, were too large to accomplish the stated objectives. Nevertheless, certain areas, such as standardization, were identified for continuing committee effort. I think JANAIR should establish permanent committees in the areas of greatest need. I also think the military test and evaluation community needs some forum to ensure that we all have the benefit of each other's efforts.

• *Mr. Blatt, Federal Aviation Administration:* The reason for the conference must center around cockpit problems. These problems, I believe, should have been listed in moderately detailed outline form sometime before the meeting so that conferees could have been better prepared for open discussion. This list would have preferably been in questionnaire form so that written comments could have been made more easily. Otherwise, long-winded, often disjointed "speeches" occur without the problem ever really surfacing.

The conference, in my opinion, was tremendous and I would hope that the proceedings will be distributed soon. I also hope that it will be followed up within a year by a second conference to determine what benefits can and have been accrued by this type of coordination. Finally, I must compliment the chairman of the displays workshop on running a well-organized, non-violent discussion.

• *Mr. Waruszewski, USAF Aeronautical Systems Division:* Although this conference did not solve my particular problem, it has been generally informative about various aspects of crew station design, human factors, and displays problems. I think these conferences are necessary to improve communications among those involved in displays and crew stations. This communication will serve to increase effectiveness in crew station design and eventual standardization, especially of CRT and other light-emitting displays.

• *Mr. Ebright, Northrop Corp.:* Too much conference time was spent on the overview papers relative to the amount of time spent in the workshop sessions. Also, the controls and displays workshop group was so large that much time was wasted in the formalities. Some of the other workshop groups could gather around a table and really exchange information and viewpoints. Smaller workshop groups would help in any future sessions.

• *Mr. Stanton, NASA Headquarters:* I believe this conference has given the vendor companies a better understanding of the government's problems. However, I believe the conference could have been organized better. First, I feel that the overall conference objectives and the objectives of the workshops could have been stated more clearly. Second, the workshops were not organized to provide efficient, productive communication. The workshops were too large and the use of company names kept participants from really letting their hair down. Perhaps a second meeting composed of a smaller number of contributors who have done their homework would be valuable.

• *Mr. McIntyre, McDonnell-Douglas Corp.:* The formal presentations--although not all produced usable data--did lead me to further believe that: multi-function CRT displays are an improvement over existing display concepts; various methodologies exist and are being further developed for use in evaluating controls and displays; and the "dedicated aircraft" is a must.

The most significant conclusions I derived from the workshop discussions are as follows: users' requirements must be made known at the outset of any research and development program if subsystem suppliers and the crew station design team are to make proper decisions; the exact value of HUDs is not established at this time; industry is capable of significantly improving controls and displays with today's technology.

My basic recommendations are: continue to use the systems approach; do not be afraid to commit a new system to use in lieu of continual improvement to the 99.9 assurance level; and provide for growth of flexibility in the crew station of new aircraft.

CLOSING REMARKS

SECTION XI

CLOSING REMARKS

• *CDR Hammack, Office of Naval Research:* At this time, I would like to acknowledge the sponsors of this conference. They participated with funding and with work as members of the steering committee. Beginning with Dave Frearson, I invite each representative to add his closing remarks to the proceedings of the conference.

• *Mr. Frearson, USAF Flight Dynamics Laboratory:* Thank you, John. I just want to make a couple of statements on behalf of the Air Force Systems Command. We have long recognized the need to achieve the stated objectives of this conference and wholeheartedly support them. It is our sincere hope that the multidisciplinary education I think we have all gained here will be transformed into action, and that the momentum that has been started will lead to achieving our objectives. We thank all of you for your enthusiasm and involvement here.

• *Mr. Anderson, NASA Headquarters:* I can only second the remarks from the Air Force. On behalf of NASA, I want to thank all of you who have made the conference successful. I am sure that as we sit back over the next few weeks and ponder all that we have heard here, it is going to have a very significant effect on our future programs in crew systems.

• *LTC Chubboy, Federal Aviation Administration:* Although I did not obtain the information that I wanted from the conference--I was seeking a methodology for determining crew workload--I feel that as a result of the conference I will now be able to come up with some ideas that will help shape this methodology. I do not know whether that is going to help our area-navigation and microwave landing system problems or not, but I am hopeful that we will at least be able to address such problems systematically. I would like to offer two suggestions. First, I think the discussants should have an opportunity to give their afterthoughts on some of the questions asked in the workshops. It might be possible for the workshop chairmen to mail a list of questions to the discussants and give the discussants a chance to prepare written responses for publication in the proceedings. Second, because time is critical, I would like to suggest that an executive summary be published in the near future which reflects the thinking and the discussion of this afternoon.

• *Mr. Wolin, Naval Air Systems Command:* I would like to take this opportunity, on behalf of the JANAIR group, to thank the participants in this symposium for their contributions. The fact that such a symposium has taken place is, in itself, significant. Remember this symposium has been sponsored by the Office of Naval Research, the Naval Air Systems Command, the Army Electronics Command, the Air Force Systems Command, the National Aeronautics and Space Administration, and the Federal Aviation Administration. It is difficult enough for one government agency to get together--can you imagine how difficult it must have been for six government agencies to get together? We have performed this miracle. The magic formula is communication. Government people working with other government people. We are hoping that government and industry can now perform the same miracle. We have here the technological ingredients required to make successful crew systems a reality. We also have among us the scientists and engineers and pilots required to create a new discipline. As you all know, in the beginning of aerospace the only disciplines were structures, aerodynamics, power plants, and instruments. As time went on areas of communication, navigation, radar, computer sciences, and so on were created as individual disciplines. They are now considered classics. I would like to propose that we consider another discipline--crew systems. I think the time is ripe for boldly announcing this fact to the scientific, engineering, and management communities. This symposium could be the catalyst in establishing such a discipline.

I am sure that when we look back on this symposium we will say that we were here and participated in the creation of a new discipline. I intend to preach this doctrine to universities, government, and industry. I would like to assure everyone here that this symposium will not be the end of our working relationship. I urge that everyone present here continue to foster the communication channels that we have started here. Please call on us--these six government agencies--at any time that you think we may be of some help.

Managers sometimes forget to say thank you for a job well done. The main reason for me getting up here today is to do just that. Thank you.

• *CDR Hammack, Office of Naval Research:* Now I will call upon Art Romero to give us his general assessment of the results of this conference.

• *Mr. Romero, Consultant:* One of the things that came out of this meeting was that although on the first day our attitude seemed to be one of self incrimination, we found we are really not as bad as we thought. Sometimes it is better to criticize ourselves than to have our higher management criticize us or take action against us.

The purpose of this conference was to promote the timely use of the best available technology in the development and evaluation of crew systems. One of the stated reasons for holding this conference was that despite the proliferation of techniques for designing or evaluating crew systems, a consolidated definition and appraisal of these techniques has never been made, nor has their proper role in the design process been determined. I do not think we quite succeeded in doing that here. But a great deal of information was brought forth that I think will pay off in the future if for no other reason than that by bringing many disciplines together we gain a better understanding of the other fellow's problems. Another conference objective was to improve communication among the many disciplines involved in the crew system design process. Probably many of our communication difficulties have resulted from the misuse or misinterpretation of words. We should make certain that we do not confuse people with specialized jargon and I think I noticed some improvement here. But the lack of communication is sometimes even more detrimental. So, I was pleased to note while observing various workshop groups that people were talking over their problems. This kind of discussion, of course, is a productive result of a conference like this.

I have noticed for some time that we tend to blame management for all our problems. I think this scapegoat approach is largely unjustified and that most of our problems arise elsewhere. It seems to me that this conference has identified two specific problem areas that underlie many of our difficulties.

First, we need more data, and we need it sooner. The standards and specifications we do get are frequently not up to date and often incomplete. But to complicate matters, the problem of data collection in our field is unusually complex. We do not have the relatively simple task of structures people, for example, who are asked to design a specified engine, of known size, to fit within a structure whose size is also known. In obtaining needed anthropometric and human performance data in some form that can be used by design engineers, we must deal with human variables and try to reduce them to some sort of common denominator. And, of course, there are many other variables in the equipment we must deal with. So, I feel this conference has helped us to realize the magnitude of our problems. It would have been better if the workshops had identified a few specific items to investigate and attempted to solve them. But, at least we must continue to seek solutions for our data problems if progress is to be made.

Second, the many disciplines in crew systems design are not unified. We need to think of our joint efforts as a *single* discipline, not broken down into human factors and the other disciplines. And this single discipline concept should be reflected organizationally in the military services and in industry. If crew systems design became a discipline in which all who contribute to the end result made their inputs cooperatively and early enough to be productively used, we would indeed be moving forward. I also endorse the suggestion that an organization outside of individual companies devoted solely to air crew systems design--similar to the Aircrew Station Standardization Panel--would be valuable.

To summarize, I think we should now return to our managements, point out the problems this conference has identified, and recommend that management consider some organizational changes. A great deal can be achieved, but it will require a great deal of effort.

• *CDR Hammack, Office of Naval Research:* I think to some degree we have been successful here. We probably need to assess what we have done and see whether we want a second conference involving management. But to some degree, at least, we have gathered some available methodologies and technologies to inform management on the state of the art in crew systems design. We did identify some promising applications of these methodologies and technologies, we did identify some present, future, and potential problems. We also then determined where we need to be. Having accomplished this and opened lines of communication between ourselves and what we previously called different disciplines, we now have to communicate with our management. Of course, we must keep working together and communicating together. I think one spinoff of the conference is the recurring theme stated by Wolf Hebenstreit and Jack Wolin, and again by Art Romero, that crew systems design should be considered as one discipline. One further question. Assuming that we can only continue to achieve our objectives by working together and communicating effectively as one unified discipline, who will take the initiative to organize a society for the crew system design engineer?

TECHNICAL PAPERS

SECTION XII

THE EFFECTS OF PERSONAL PROTECTIVE EQUIPMENT UPON THE ARM-REACH CAPABILITY OF USAF PILOTS

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DR. LLOYD L. LAUBACH
WEBB ASSOCIATES

Abstract: *The lack of published arm-reach data on Air Force flight personnel in actual cockpit situations presents manifest difficulties to the cockpit layout specialist. This paper discusses the results of a study to determine the arm-reach capabilities of aircrewmen wearing heavy winter flight clothing, survival equipment, and restraint harnesses.*

The study was conducted at Loring AFB, Maine. The sample consisted of 16 male subjects (currently active Air Defense Command pilots). The subjects were selected to approximate closely the various height-weight categories in the ADC flying population. A specially designed apparatus was constructed to measure arm-reach capability. Each subject was measured under four conditions: (1) shirt-sleeved with the inertial reel unlocked, (2) shirt-sleeved with the inertial reel locked, (3) wearing his full assembly of flying gear (hereafter referred to as maximum assembly) including the underarm life preserver and parachute harness with the inertial reel unlocked, and (4) wearing the maximum assembly with the inertial reel locked.

The results of the study indicated that there are significant differences in arm-reach capability of pilots while in the shirt-sleeved and maximum flying assembly conditions throughout most of the spatial envelope.

The lack of published arm-reach data on Air Force flight personnel in simulated cockpit situations presents manifest difficulties to the cockpit layout specialist. This paper will present results of a study that was designed to determine the arm-reach capabilities of USAF pilots wearing heavy winter flight clothing, survival equipment, and restraint harnesses. Obviously, such equipment and conditions do have an effect on the design of cockpits.

The study was conducted at Loring Air Force Base, Maine to assure acquisition of currently active USAF pilots flying operational missions for the Air Defense Command. The test sample was specifically chosen to simulate the various body-size categories of the Air Defense Command flight population. The sample consisted of 16 pilots whose mean age was 33.4 years, ranging from 25 to 46 years; mean height of 69.3 inches, ranging from 66.6 inches to 73.4 inches; and a mean weight of 179.2 pounds, ranging from 145 to 238 pounds.

The test apparatus, illustrated in Figure 1, was designed to measure the arm-reach capability of the subjects and is basically composed of three main components.

The *seat* (see a in Figure 1) is designed in accordance with Military Standard DH2-2, incorporating five inches adjustability, ±2½ inches from the neutral seat reference point along a 13° back angle. It is equipped with adjustable shoulder restraint harnesses and lap belts which are standard equipment in many USAF cockpits.

The *overhead boom* (see b in Figure 1) is mounted above the seat and is anchored to the frame of the measuring apparatus. It rotates horizontally about an axis through the seat reference point. Its rotation covers an arc of 180° forward of the seat (90° to the right and 90° to the left of a vertical plane perpendicular to the seat pan and passing through the seat reference point to bisect the seat pan) with stops at 30° intervals. Located on the horizontal arm of the overhead boom is a measuring scale with its origin directly vertical to the seat reference point. This scale is graduated in ¼-inch increments from zero inches to 54 inches.

The *vertical rod* (see c in Figure 1) is attached to the horizontal arm of the overhead boom and is capable of fore-aft movement. Standard control knobs are mounted on the vertical rod and are spaced six inches apart beginning six inches above the deck to a height of 60 inches.

An additional knob (see c' in Figure 1) is placed on a separate but corresponding vertical arm at a height of 63 inches above the deck.

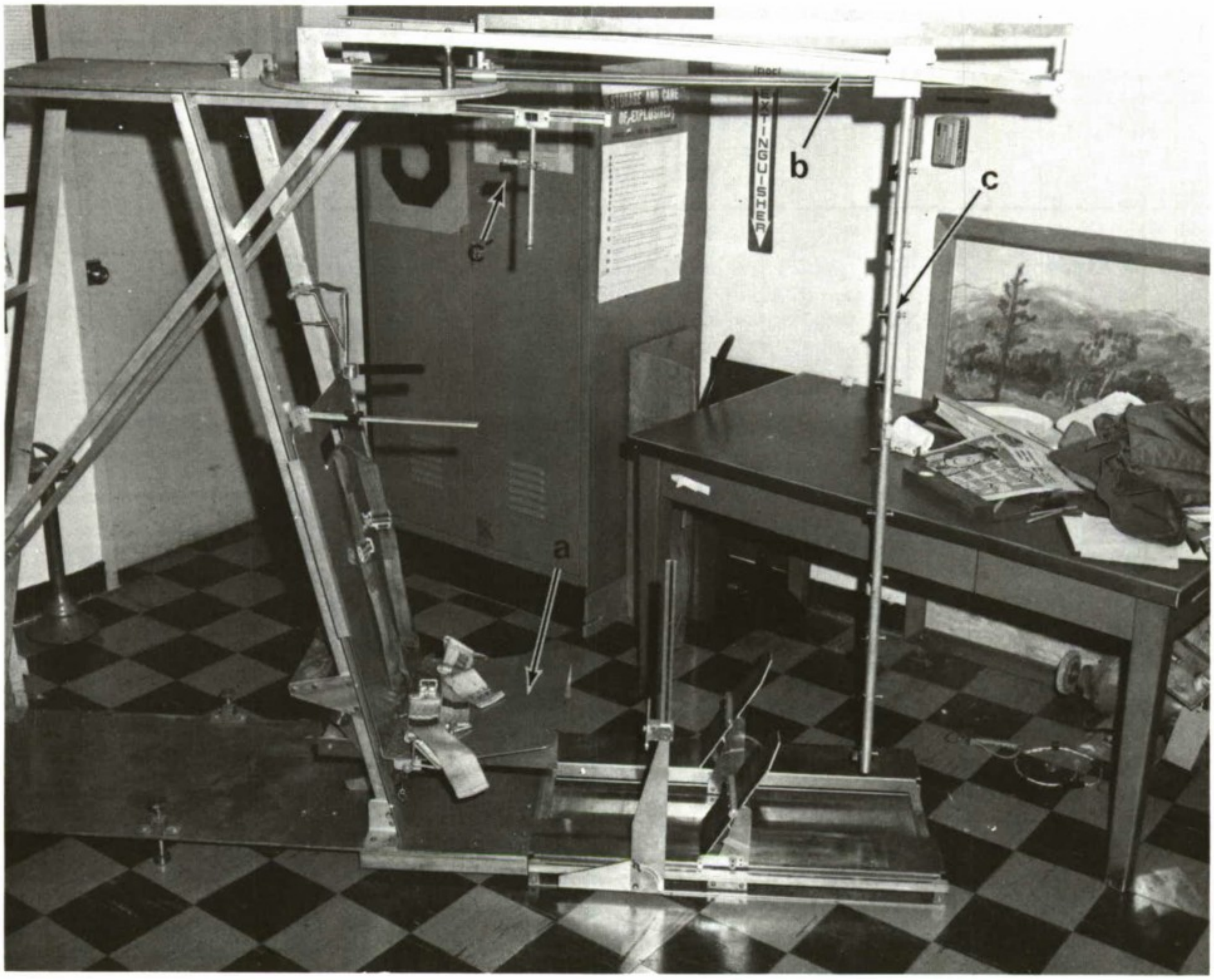


Figure 1. The arm-reach apparatus.

Figure 2 illustrates the personal protective equipment worn by the pilot subjects during the test to determine the arm-reach capability measurements in the encumbered conditions. This assemblage of flight gear is representative of what is worn by Air Defense Command pilots during cold weather missions. It should be noted that the subjects wore the flight gear and garments in accordance with their personal needs.

The reach envelope of each subject was measured under four conditions: (1) shirt-sleeved with the inertial reel unlocked, (2) shirt-sleeved with the inertial reel locked, (3) full assembly with the inertial reel unlocked, and (4) full assembly with the inertial reel locked. The sequence of reach procedure and the knob distances from the deck are illustrated in Figure 3.

Figure 4 illustrates a subject in the arm-reach machine wearing his complete flying assembly. The subject, with the inertial reel locked, grasps the control knob at the 24-inch level at the position of L60° (left hand at 60° from the seat reference point).

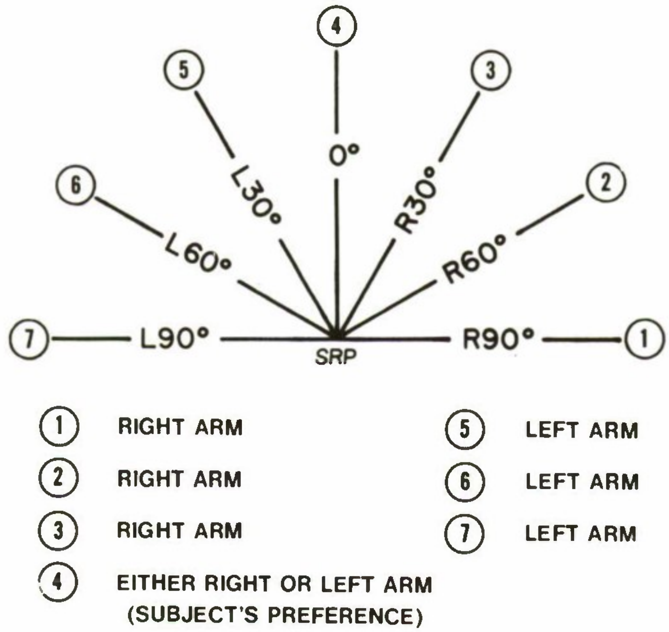
Figure 5 indicates a subject, with the inertial reel locked, reaching and actuating a control knob at the R90°, 60-inch level (right arm at 90° from seat reference point reaching a knob located 60 inches above deck height).

Figure 6 illustrates a subject, with the inertial reel unlocked, reaching with his left hand at 30° from seat reference point at 42 inches above deck height.

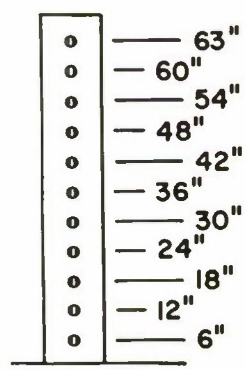
Figure 7 presents tabular and graphical data for one of the selected arm-reach measurements. This particular illustration presents mean (average) data for the 16 subjects at the 54-inch level with the inertial reel in the unlocked position. It is to be interpreted as follows: e.g., with the inertial reel in the unlocked condition at the position of R30° (right arm actuating control knobs at

Figure 2. Personal protective equipment.

SEQUENCE OF REACH PROCEDURE



KNOB DISTANCES FROM DECK



SUBJECT BEGINS AT 6" LEVEL
AND PROCEEDS TO THE 63" LEVEL

Figure 3. Sequence of reach procedure and knob distances from deck.

Figure 4. Subject in test apparatus wearing complete flying assembly

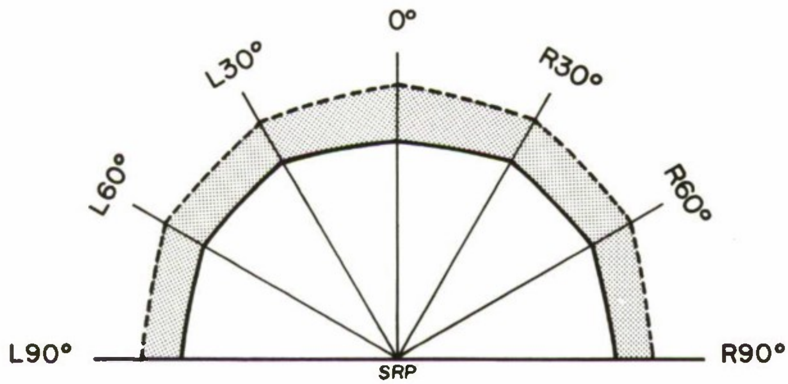
Figure 6. Subject in test apparatus with inertial reel unlocked.

Figure 5. Subject in test apparatus with inertial reel locked.

30° from seat reference point), the mean value for the shirt-sleeved condition was 29.70 inches and the mean value for the maximum assembly condition was 24.80 inches. This condition resulted in a 4.90-inch decrement (Δ) and a percentage difference of 83.5.

The graphical display of the data is an attempt to present an actual arm-reach envelope from the tabular data. The dashed (---) line of the illustration indicates the distances reached from the seat reference point (SRP) while being tested in the shirt-sleeved condition. The solid (——) line indicates the distances reached while the subject wore the maximum assembly of flying gear. The hatched (▬) area indicates the difference between the two conditions. Inspection of Figure 7 indicates differences ranging from 4.22 inches (R90° position) to 6.03 inches (0° position) from the shirt-sleeved to the maximum assembly condition.

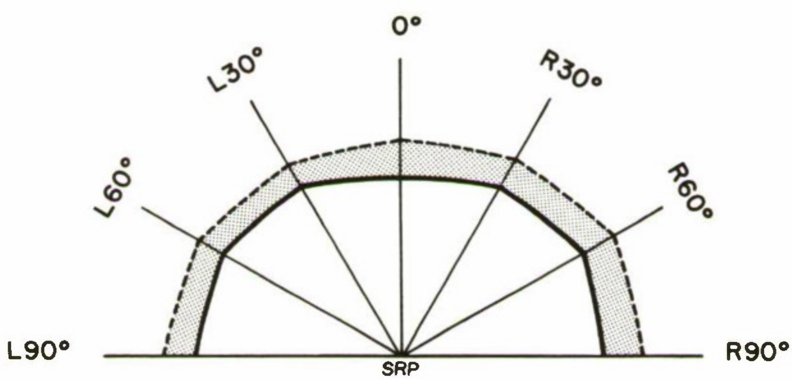
Figures 8, 9, 10, 11, and 12 are similar tabular and graphical illustrations that were randomly selected examples of arm-reach data gathered in this study. Inspection of these figures indicates the magnitude of differences between the shirt-sleeved and the maximum assembly conditions. It is interesting to note that the differences in arm-reach capability tend to decrease as the control knob distances



	SHIRT SLEEVED	MAXIMUM ASSEMBLY	Δ	%
R 90°	27.95	23.73	4.22	84.9
R 60°	29.53	24.36	5.17	82.5
R 30°	29.70	24.80	4.90	83.5
0°	29.59	23.56	6.03	79.6
L 30°	29.63	24.72	4.91	83.4
L 60°	29.02	24.28	4.74	83.7
L 90°	27.80	23.38	4.42	84.1

* All measurements in inches

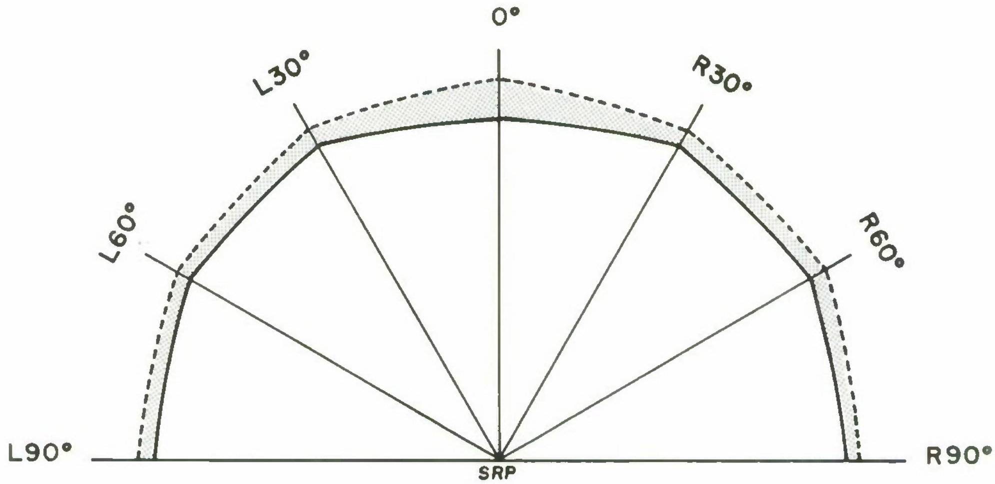
Figure 7. Tabular and graphical arm-reach measurements (unlocked inertial reel--54" level).



	SHIRT SLEEVED	MAXIMUM ASSEMBLY	Δ	%
R 90°	26.14	21.91	4.23	83.8
R. 60°	26.64	22.77	3.87	85.5
R 30°	24.78	21.41	3.37	86.4
0°	23.69	19.44	4.25	82.1
L 30°	24.20	21.47	2.73	88.7
L 60°	25.39	22.39	3.00	88.2
L 90°	25.86	22.08	3.78	85.4

* All measurements in inches

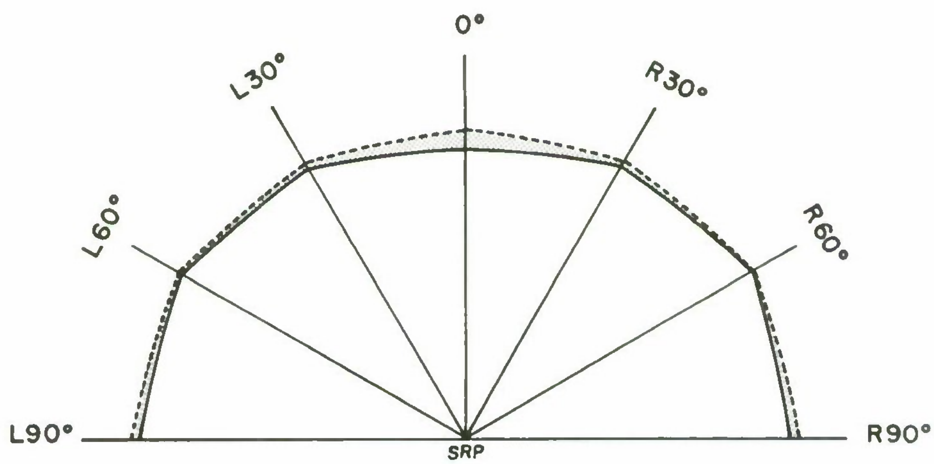
Figure 8. Tabular and graphical arm-reach measurements (locked inertial reel--54" level).



	SHIRT SLEEVED	MAXIMUM ASSEMBLY	Δ	%
R 90°	39.14	37.81	1.33	96.6
R 60°	41.03	39.05	1.98	95.2
R 30°	41.11	39.03	2.08	94.9
0°	41.13	36.73	4.40	89.3
L 30°	41.09	39.11	1.98	95.2
L 60°	40.33	38.78	1.55	96.2
L 90°	39.09	37.19	1.90	95.1

* All measurements in inches

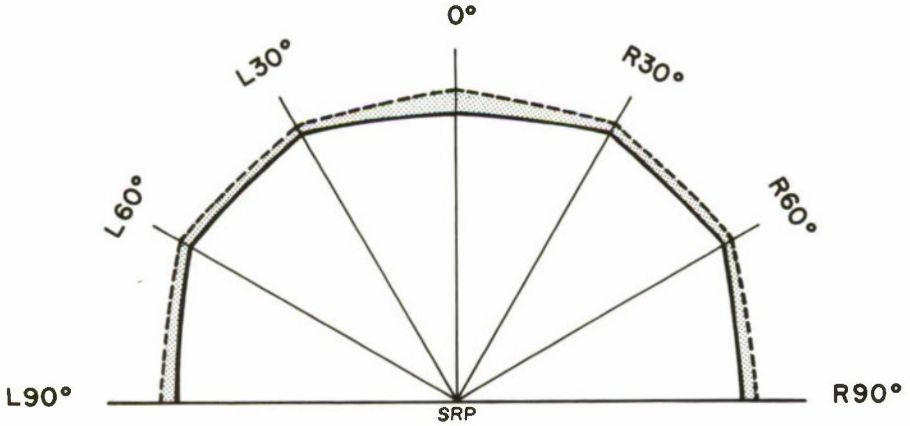
Figure 9. Tabular and graphical arm-reach measurements (unlocked inertial reel--36" level).



	SHIRT SLEEVED	MAXIMUM ASSEMBLY	Δ	%
R 90°	36.09	35.31	.78	97.8
R 60°	36.06	35.98	.08	99.8
R 30°	34.81	34.03	.78	97.8
0°	33.69	31.44	2.25	93.3
L 30°	34.61	33.84	.77	97.8
L 60°	35.83	35.28	.55	98.5
L 90°	36.05	35.11	.94	97.4

* All measurements in inches

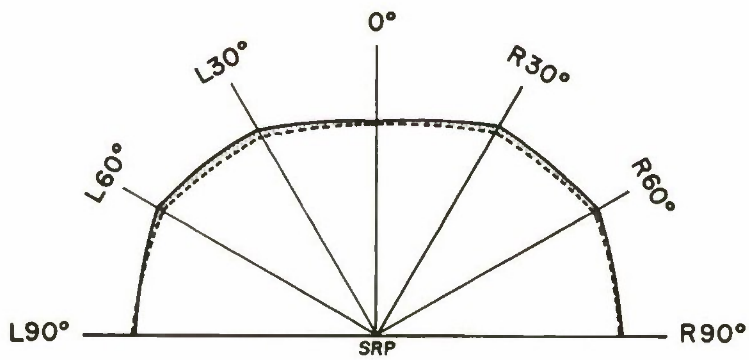
Figure 10. Tabular and graphical arm-reach measurements (locked inertial reel--36" level).



	SHIRT SLEEVED	MAXIMUM ASSEMBLY	Δ	%
R 90°	32.70	31.08	1.62	95.0
R 60°	34.78	33.70	1.08	96.9
R 30°	34.72	33.52	1.20	96.5
0°	33.77	31.11	2.66	92.1
L 30°	34.52	33.41	1.11	96.8
L 60°	34.80	33.59	1.21	96.5
L 90°	32.13	30.66	1.47	95.4

* All measurements in inches

Figure 11. Tabular and graphical arm-reach measurements (unlocked inertial reel--6" level).



	SHIRT SLEEVED	MAXIMUM ASSEMBLY	Δ	%
R 90°	26.25	26.S6	-.31	101.2
R 60°	27.11	27.86	-.75	102.8
R 30°	2S.S9	26.09	-.50	102.0
0°	23.13	23.11	.02	99.9
L 30°	25.06	25.89	-.83	103.3
L 60°	26.86	27.58	-.72	102.7
L 90°	26.56	26.44	.12	99.5

* All measurements in inches

Figure 12. Tabular and graphical arm-reach measurements (locked inertial reel--6" level).

approach deck level. In fact, the subjects were able (see Figure 12) to reach approximately the same distances in both the shirt-sleeved and the maximum assembly conditions at the six-inch level with the inertial reel locked (actually further at the positions of R90°, R60°, L30°, and L60°).

In summary, the results of the study indicate that there are significant differences in arm-reach capability of pilots while in the shirt-sleeved and maximum flying assembly conditions throughout most of the spatial envelope. These differences seem to be the greatest for the control knobs located highest from the deck and tend to decrease for those knobs approaching deck level.

In general, also, the arm-reach capability of a subject reaching directly in front of his body (designated 0° in this study) yields smaller values than for other positions in this study. The primary reason for this seems to be that the shoulder harness straps severely limit the mobility of the arm/shoulder complex in a position directly in front of the operator.

Cockpit layout specialists should be aware of the differences in arm-reach capabilities of pilots wearing light weight flying clothing (shirt-sleeved) and heavy winter flying assemblies. These differences should be considered in the placement of controls and switches in cockpit design.

A complete presentation of the data for all angles and knob levels will be forthcoming in a USAF technical report.

ACKNOWLEDGMENTS

The authors wish to thank Mr. John W. Garrett for his participation in all phases of the study. LtCol. David Leavitt, Air Defense Command, USAF, deserves the thanks of the authors for handling the administrative details at Loring Air Force Base. Dr. Melvin Warrick and Charles E. Clauser, Human Engineering Division, reviewed the manuscript and offered valuable suggestions. Special appreciation is extended to Dr. John T. McConville, Webb Associates, for his help and encouragement throughout the study.

AN OPTIMIZATION TECHNIQUE FOR THE NUMBER/TYPE OF COCKPIT CONTROLS

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Abstract: *The selection of the optimum number/type of cockpit controls is a major design problem. This paper describes a linear programming technique that provides a means of comparing many control configurations and yields guidelines for selecting the best one.*

Linear programming deals with the problem of allocating limited resources among competing activities in an optimal manner. The procedure requires the development of a mathematical model that represents all aspects of the problem.

Two models will be described using graphical solutions to aid in visualization of the concept. In addition, a generalized mathematical model is developed specifically for application to cockpit controls.

INTRODUCTION

Linear programming is an established technique that has:

- Helped farmers increase profits by indicating how much of each crop to plant.
- Aided dieticians in planning nutritious meals at minimum cost.
- Solved some of the military logistics problems, starting in World War II.

It can be applied to cockpit control systems to determine the "best" configuration of a particular control subsystem. "Best" may mean:

- Lowest cost,
- Easiest to operate,
- Minimal training time, and/or
- Most reliable/maintainable.

The methods of solving linear programming problems have been available since World War II. George B. Dantzig (1963) carried out an analysis of military logistics problems and proposed that the interrelationships of the activities of a large organization be viewed as a type of model of linear programming. The "best" course of action is determined by minimizing (or maximizing) a linear function.

TYPICAL EXAMPLE

This technique will be described by presenting examples. The first is a daily type of problem; the second has to do with a simple control system.

You, as a discerning shopper, want to buy enough food so your family gets all the nutrients they need, and you also want to minimize your cost. For today, you have two cereals to choose from as your family's source of thiamin, phosphorus, and iron. The comparison is as follows:

	CEREAL A	CEREAL B	MDR
Thiamin (mg/oz)	.15	.10	1
Phosphorus (mg/oz)	75.0	170.0	750.0
Iron (mg/oz)	1.30	1.10	10.0
Cost Per Ounce	6¢	5¢	

It's easy to see that buying ten ounces of either cereal will satisfy the minimum daily requirement (MDR) and that the cheaper plan would be to buy ten ounces of B for 50 cents. But maybe there is a way of buying a mix of A and B that is even more cost effective. Certain assumptions are made:

- It is possible to buy fractional quantities of cereal.
- The family is willing to consume one or both of the cereals.
- It doesn't matter if they receive more than the MDR of one nutrient.

Let a and b represent the amount (in ounces) of cereals A and B that is bought. You must get at least 1.00 mg of thiamin, so:

$$.15a + .1b \geq 1 \qquad (1)$$

Similarly, for phosphorus

$$75a + 170b \geq 750 \qquad (2)$$

and for iron

$$1.3a + 1.1b \geq 10 \qquad (3)$$

Since it is impossible to buy negative quantities of cereal:

$$a \geq 0, \quad b \geq 0 \qquad (4)$$

The problem is to pick a and b such that the above constraints are met, and that the cost, represented by:

$$K = 6a + 5b \qquad (5)$$

is minimized.

The constraints form a set of acceptable, or feasible, solutions. The pair (a = 10, b = 10) satisfies the constraints, while the pair (a = 2, b = 2) does not. One way of visualizing this simple example is by examining the constraints shown graphically in Figures 1 and 2. The shaded area contains all the point pairs where the constraints are satisfied.

If an arbitrary point is chosen (refer to Figure 2) in this area, say a = 5, b = 6, the line representing 6a + 5b = 60 can be drawn which passes through this point. If this line is moved toward the origin (always keeping it in the form 6a + 5b = K), the cost is decreased until the boundary of the constraint region is reached. It is impossible to go further in the direction of reducing costs without leaving the feasible solution space, and it is apparent that the optimal feasible solution has been obtained.

It is also seen that the cost is 46 cents, which is a definite improvement over 50 cents for ten ounces of B or 60 cents for ten ounces of A.

This problem could have also been solved using the simplex method, which is strictly a mathematical approach. This method is shown later in the paper. Further information on the simplex method and its variants can be found in detail in Dantzig (1963).

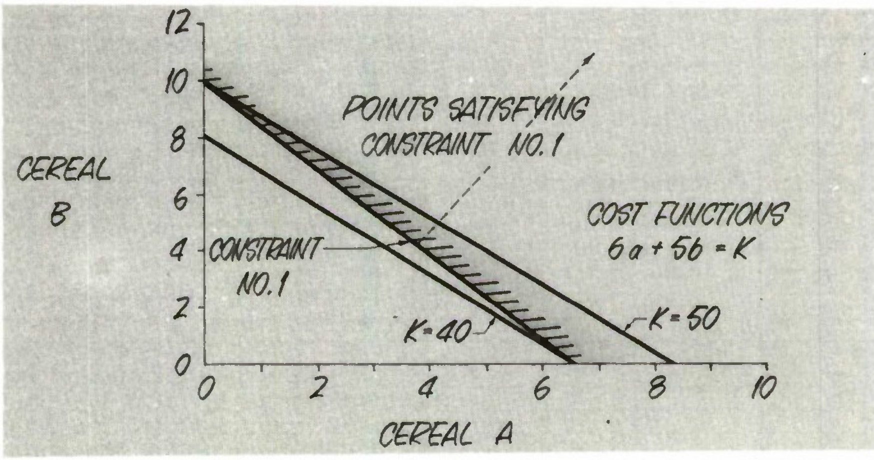

Figure 1. Cost versus one constraint.

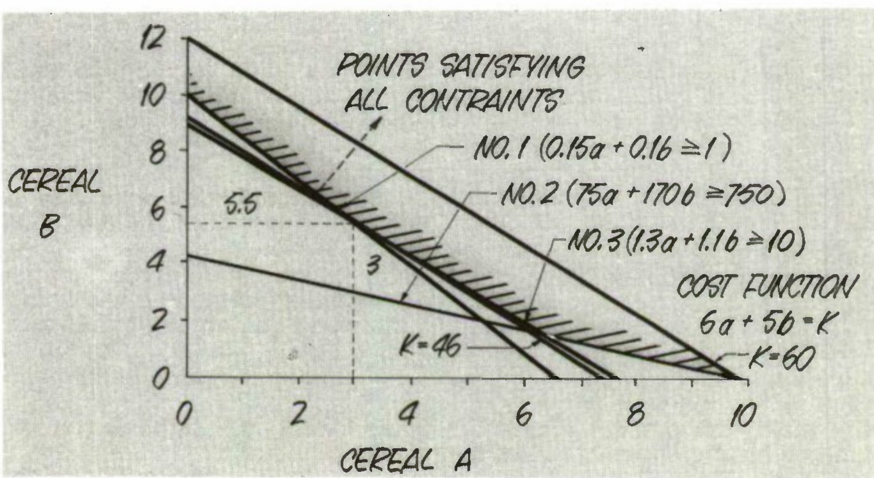

Figure 2. Cost versus three constraints.

From the nutritional problem, we can go on to other common classes of linear program problems--the transportation problem, optimal-assignment problem, and the catering problem. However, these can be found in any one of several texts (Dantzig, 1963; Mathews & Langenhop, 1966; Hillier & Lieberman, 1970; Vajda, 1961).

CONTROL PANEL EXAMPLE

We will now apply this powerful tool to the problem of determining the number and type of cockpit controls. Let's examine a simple case of controls.

Consider a control panel (Figure 3) consisting of toggle switches and that we have a choice of using single throw (ST) or double throw (DT) switches. The limiting factors for our selection are panel space, number of functions required, total number of switches, and total number of dedicated switches. We want to design a control panel that will:

1. Contain a maximum of 20 switches.
2. Occupy no more than 48 square inches. An ST switch needs two square inches; a DT switch needs three square inches.
3. Have a maximum capacity of 30 functions. It is assumed that an ST switch can be used for one function, a DT switch for two functions.
4. Have at least two dedicated functions, i.e., functions requiring an ST switch.
5. Have at least one either-or function--a condition that requires a DT switch. Note that the usual non-negativity constraints have been superseded by 4 and 5, requirements for a minimum.
6. Have a minimum capacity of 20 functions.

It is nice to develop constraints, but what is it that we are trying to optimize? It could be:

Profit--we made 1.3 times more if we use DT switches, because they allow more markup and require less assembly time.

or

Pilot preference--pilots, in the ratio of 1-2/3:1, favor DT switches over ST switches. A pleased pilot makes a product more saleable.

Let x_1 = number of ST switches used

x_2 = number of DT switches used

The constraints can be represented as:

$x_1 + x_2 \leq 20$ maximum number of switches (6)

$2x_1 + 3x_2 \leq 48$ maximum panel space (7)

$x_1 + 2x_2 \leq 30$ maximum number of functions (8)

$x_1 \geq 2$ minimum number of required ST functions (9)

$x_2 \geq 1$ minimum number of required DT functions (10)

$x_1 + 2x_2 \geq 20$ minimum number of functions (11)

and the two objective functions we want to maximize are:

$$\text{profit} = x_1 + 1.3x_3 \qquad (12)$$

$$\text{pilot preference} = x_1 + 1.67x_2 \qquad (13)$$

Visualizing these constraints on a graph (Figure 3), we can see the area containing the feasible solutions. The two objective functions to be optimized (maximized) are drawn in at their respective optimum feasible solution points.

Note that the maximum value of (12) is obtained at (x_1 = 12, x_2 = 8) while the maximum value of (13) is obtained at (x_1 = 6, x_2 = 12). This shows that optimizing different objective functions over the same constraints can result in different optimum feasible solutions. In the case of the profit function, the driving constraints were (6) the maximum number of switches and (7) the maximum amount of panel space. This implies we want to fill up the space with the most profitable switches and still satisfy the constraints.

Similarly, the pilot preference function tries to fit most of the DT switches in the available panel space (constraint 7) while not exceeding the limit on the number of functions allowed (constraint 8).

Thus, the optimal feasible solution of the profit function results in a panel containing 28 functions at a profit of 22.4, while the optimal feasible solution of the pilot preference function results in a panel of 30 functions, but at a profit of only 21.6. The guidelines have been established--the designer has to choose what the final configuration should be. If this technique is applied to larger and more complex control panels (involving three or more unknowns), the graphical method is unusable. The simplex method, or one of its variants, must be used. This involves putting the problem into a standard general form.

GENERALIZED MATHEMATICAL FORM

Find $x_1, x_2 \ldots, x_n$ which maximizes the linear function

$$z = c_1x_1 + c_2x_2 + \ldots + c_nx_n$$

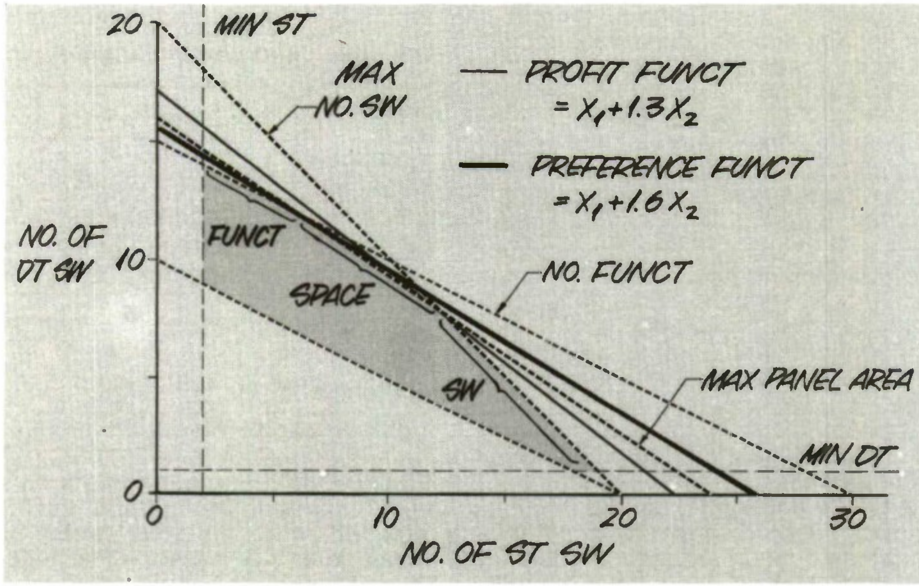

Figure 3. Control panel example.

subject to the constraints

$$a_{11}\,x_1 + a_{12}\,x_2 + \ldots + a_{1n}\,x_n \leq b_1$$

$$a_{21}\,x_1 + a_{22}\,x_2 + \ldots + a_{2n}\,x_n \leq b_2$$

$$\vdots$$

$$a_{m1}\,x_1 + a_{m2}\,x_2 + \ldots + a_{mn}\,x_n \leq b_m$$

and $x_1 \geq 0,\ x_2 \geq 0,\ \ldots,\ x_n \geq 0$

This means that given n competing activities, the decision variables $x_1, \ldots x_n$ represent the level of these activities. In this case, the activity is the selection of the types of controls, and x_j would be the number of the jth type of control to be incorporated in the panel design. z is chosen to measure the overall effectiveness (e.g., the ease of operation). c_j is the increase in the overall measure of effectiveness that would result from the unit increase of x_j. There are m relevant resources, so that each of the first m linear unequalities corresponds to a constraint on the availability of one of the resources (e.g., available panel area, software support, weight). b_i is the amount of resource i available to the n components. a_{ij} is the amount of resource i that each component of the jth type consumes. Therefore the left side of the inequalities is the total usage of the respective resources. The nonnegativity restrictions ($x_j \geq 0$) rule out the possibility of a negative number of components.

THE SIMPLEX METHOD

One key to the successful application of linear programming to a control panel is the ability to recognize when a control panel problem can be adapted to obtain a solution by this technique and then to formulate the problem as shown above. The simplex method can then be applied to the problem and will indicate if:

- An optimal feasible solution exists (and its value).
- No feasible solution exists.
- The feasible solutions are unbounded

The last two cases usually mean that the problem was incorrectly stated or that the constraints must be altered to achieve a solution. If we take the toggle switch problem, using the pilot preference function, we have:

maximize: $z = x_1 + 1\frac{2}{3}\,x_2$

subject to: $x_1 + x_2 \leq 20$

$x_1 + 2x_2 \leq 30$

$2x_1 + 3x_2 \leq 48$

Note that some of the constraints are omitted. Since we know the constraints in the general vicinity of the solution, we can limit ourselves to those constraints to help simplify the presentation of the problem.

If we change the form of z by multiplying by 3/5 (to dispose of the fractional form), we get:

$$z = .6x_1 + x_2 \tag{14}$$

The next step is to introduce auxiliary, or slack, variables into the constraints so we

can start the simplex method with a basic feasible solution.

$$x_1 + x_2 + x_3 = 20 \quad (15)$$

$$x_1 + 2x_2 + x_4 = 30 \quad (16)$$

$$2x_1 + 3x_2 + x_5 = 48 \quad (17)$$

We see that $x_1 = 0$, $x_2 = 0$, $x_3 = 20$, $x_4 = 30$, $x_5 = 48$ is a basic feasible solution, but it results in a value of $z = 0$. The next step is to set up a table, or tableau, of these values to make it easier to work with the numbers.

TABLE 1

INITIAL TABLEAU

VARIABLE	x_1	x_2	x_3	x_4	x_5	CONSTANTS
z	-.6	-1				0
x_3	1	1	1			20
x_4	1	2		1		30
x_5	2	3			1	48

Now we must determine which of the non-basic variables (x_1 or x_2) will enter (i.e., be introduced into) the new basic feasible solutions. This is done by examining the coefficients of the "cost" function, z, to see which one has the most negative value. In this case, x_2, with a value of -1, has the most negative value.

Next, replace one of the variables in the present basic solution by x_2. The one that is selected is the one that reaches zero first as the new entering variable is increased. If we rewrite equations (15), (16), and (17) in terms of x_2 and the present basic variables (x_1 is set to zero since it is non-basic), we get:

$$x_3 = 20 - x_2 \quad (18)$$

$$x_4 = 30 - 2x_2 \quad (19)$$

$$x_5 = 48 - 3x_2 \quad (20)$$

As x_2 increases and reaches a value of 15, equation (19) reaches zero first. So x_2 replaces x_4 as a basic variable.

Performing a Gauss-Jordan elimination to do this, we get Table 2. This process is repeated, but by looking at Table 2 to make the necessary decisions. x_1 is chosen as the entering variable (its coefficient is -0.1), and x_5 is chosen to leave (it is driven to zero when $x_1 = 6$). Replacing x_5 with x_1, we get Table 3. This is the final tableau because none of the coefficients in the cost expression are negative. The basic feasible solution that results from this tableau should

TABLE 2

INTERMEDIATE TABLEAU REPLACING x_4 BY x_2

VARIABLE	x_1	x_2	x_3	x_4	x_5	CONSTANTS
z	-.1	0		.5		15
x_3	.5	0	1	-.5		5
x_2	.5	1		.5		15
x_5	.5	0		-1.5	1	3

TABLE 3

FINAL TABLEAU REPLACING x_5 BY x_1

VARIABLE	x_1	x_2	x_3	x_4	x_5	CONSTANTS
z	0	0		.2	.2	15.6
x_3	0	0	1	1.0		2
x_2	0	1		2.0		12
x_1	1	0		-3.0	2	6

be the optimal feasible solution. We can pick out the solution $x_1 = 6$, $x_2 = 12$, $x_3 = 2$, $x_4 = 0$, $x_5 = 0$ and see that this corresponds to the graphical solution found from Figure 3. The only difference is that it results in setting x_3, an auxiliary variable, equal to a positive quantity. But this means that we are not using all of the available resource allowed in the constraint involving x_3 (e.g., equation 15). In fact, the panel is only using 18 switches ($x_1 + x_2$), and x_3 (the auxiliary variable) must equal two for equation (15) to be valid.

As seen from the above example, the simplex method is a very mechanical procedure, well suited to computer solution. Thus, more complex control panels can be optimized using the mathematical method, allowing freedom to examine 30 or 40 different types of controls for a given problem.

CONCLUSION

The examples presented illustrate how the technique of linear programming can be applied to simple control panels (subsystems). Extending this technique we can optimize the configuration of large, complex control systems. This does not mean that the design committee (consisting of design engineers, life science engineers, and pilots) is not required. It means that the design committee should set up the constraints and the functions to be optimized, and let linear programming do the rest.

It should be noted that linear

programming is only a design tool, and that the answers it provides should be analyzed to see if they are logical, consistent, and useful. If not, the constraints and/or objective functions should be changed and the process repeated.

Panels designed using this technique are more likely to survive without major changes because more variables can be taken into account and more configurations can be examined while arriving at the final design.

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A TECHNIQUE FOR ASSESSING OPERABILITY/EFFECTIVENESS OF CONTROL-DISPLAY SYSTEMS

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Abstract: *In the past, both time-line analysis and dynamic-simulation techniques have been used to evaluate the overall effectiveness of a crew station design, but only after the system is well along in the development cycle. This paper describes a computerized technique for evaluating the relative operator load within a realistic mission context. The technique is called the time-based load analysis (TBLA). The advantage of this approach is that a feedback on the control-display design effectiveness is possible very early in the development cycle. If changes are required, it is much easier to effect them early in the design process rather than when the program is reaching its maturity. In summary, the TBLA:*

- *Provides assessment of operator/avionic system mechanization--short of simulation or actual flight.*
- *Provides a diagnostic technique for assessing overall crew/system effectiveness.*
- *Isolates operator overload situations.*
- *Allows feedback into crew station layout for correction purposes.*
- *Puts the entire mission into an operating context.*
- *Provides guidance on test and evaluation areas.*
- *Evaluates the impact of contingencies on operator performance*

INTRODUCTION

For many years the major validation of both the avionic and airframe design of a new vehicle, short of flight test, has taken place in a simulator, where the actions and decisions of the operator in concert with the system can be tested in a quasi real-life context. Simulator test runs offer valuable information to the design team and the training specialist in their efforts toward providing an effective total system mechanization. They are costly to mechanize, and in an era of cost-conscious customers can only be used on the very large or highly experimental programs. In the design phases preceding simulation, however, there has been little developed over the years in the way of techniques that provide an assessment of operability at the design requirements level.

The discussion that follows will point out an innovative technique that has been developed at Litton Systems, Guidance and Control Systems Division, that appears to offer potential in the assessment of control-display system operability. The technique, which is called the time-based load analysis (TBLA), is a computer-based analysis tool that provides a relative assessment of operator load within a mission context against a time line.

OPERATOR WORKLOAD

Before examining the techniques available to study operator workload, a review of the major work loading factors is in order. The major burdening factors that impinge on the operator in an aircraft are summarized in Figure 1.

Current weapon systems and reconnaissance aircraft are on the verge of almost complete saturation of the processing capabilities of the human operator. The addition of more sophisticated sensors, still higher performance aircraft, and more effective enemy defenses all underscore the need for a more effective way of unburdening the operator to insure mission success and safety. For example, during a typical weapon-release activity of a high-speed, low-altitude run, the pilot must fly the aircraft safely, search and acquire the target with sensors, lock on, select a weapon, release the weapon, determine the extent of ECM to be employed, monitor critical avionic parameters, and make damage assessment all in a matter of seconds.

Historically, this problem has been magnified by the development of better and better avionic "black boxes," and higher performance aircraft. However, this development

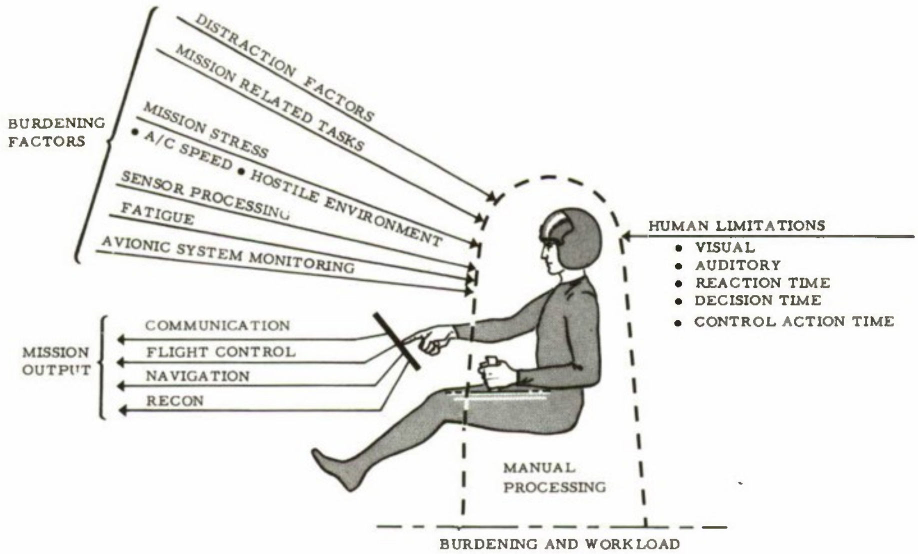

Figure 1. Summary of operato burdening and workload.

was largely nonintegrative. That is, the total requirements of the weapon system were not considered on an integrative basis in terms of the avionic system design *and* the operator.

One way of counteracting this situation is to analyze the potential effects of operator workload versus mission requirements early in the design phase, and before simulation. By examining the relative workload throughout a demanding mission, the function/task allocation, control/display mechanization, and cockpit layout can hopefully be optimized.

TECHNIQUES AVAILABLE FOR LOAD ANALYSIS

Classically, line analyses have been used *after* a system has been mechanized for evaluation purposes. Other techniques have been developed which postulate human reliability estimates against a time base. Still others have attempted to weight the workload at a mission segment level. In general, they have largely been manually set up and executed.

Litton became intrigued with the analytic possibilities of a computer-based dynamic operator load analysis during its involvement with the Integrated Cockpit Research Program in 1966. Figure 2 shows an early attempt at a time-line load analysis in which the actions and discussions of the operator were analyzed with respect to the particular controls and displays he was working with at a given time. In essence the diagram provides a look at the overall involvement of the operator at any given time. An assessment of load was made manually by looking at the total number of decisions he must make while simultaneously performing control and display activities.

The analysis suffered from a lack of appropriate load estimates--the analyst was forced to make an assessment based on his own expertise. In addition, the analysis was cumbersome to fill out, encode, and reproduce, and it did not allow any flexibility with respect to changes, additions, or deletions of functions.

At this point, several factors were explored which led to the Litton TBLA as it is now constituted:

- Storage of function/tasks on the computer.
- Use of the computer to manipulate the analytically derived actions of an operator based upon a previously established list of criteria.
- Use of the computer to printout the analysis in hard copy form.

In order to understand the TBLA more fully, it is necessary to look at the structure of a control-display methodology which is integral to the utilization of the TBLA.

BASIC ANALYTIC APPROACH

The basic approach developed at Litton Systems, Guidance and Control Systems Division is shown in Figure 3. The TBLA is the outgrowth and the final ingredient of a systematic analytic process that has at its root the derivation of mission requirements. Without the structure of a mission-related control/display system, the analysis would be impossible. That is to say, that every control and display requirement should have a generic tieback to specific mission requirements.

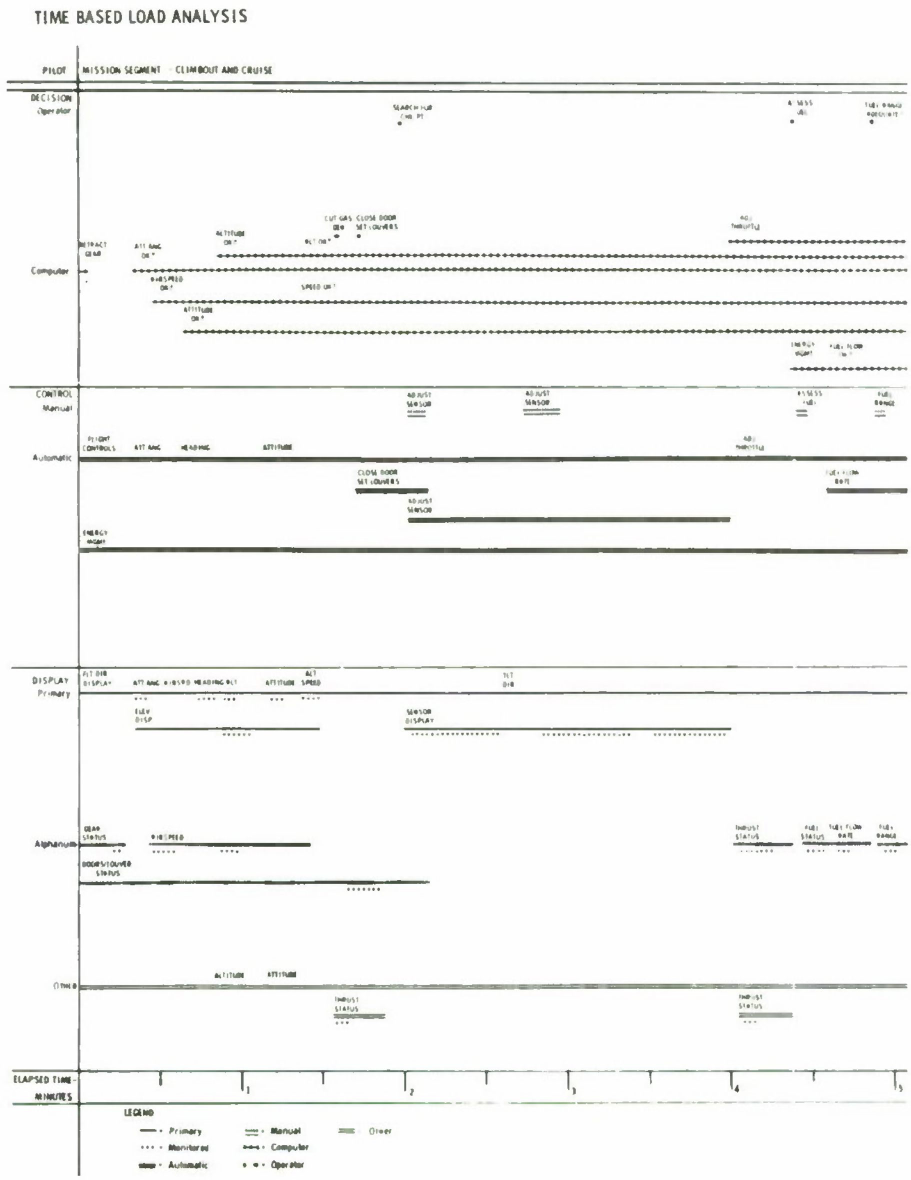

Figure 2. Time-based load analysis.

ANALYTIC STEPS PRECEDING TBLA

After the mission requirements have been derived, every function is identified that is necessary to perform the mission. If the mission is a conceptual one in which no specific hardware has been postulated, then the functions are derived. If some equipment has been selected, the functional aspects of the equipment are utilized along with those that are not.

An allocation of the function is next made to the system or the operators and the associated tasks derived.

The next step is to obtain specific control and display requirements based on each function or task in a mission context. After these requirements are derived, a mechanization is suggested.

Concurrent with the requirements analysis, a variety of crew station layouts are explored, mockups built and evaluated. A final layout based on the control-display requirements and the physical aspects of the cockpit enclosure and operators is then made.

TIME-BASED LOAD ANALYSIS (TBLA) PROCESS

The derived system is now ready for evaluation. A general overview of the TBLA process is shown in Figure 4. Again it should be stressed that the TBLA is a direct outgrowth of the analytic process and cannot be

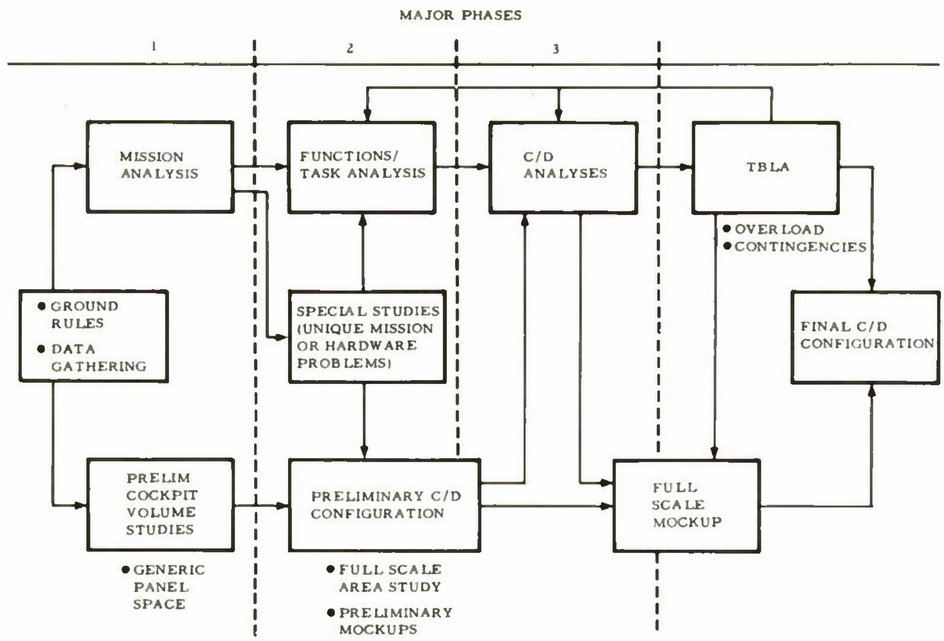

Figure 3. Control-display system methodology.

applied to a program without the systematic steps previously listed.

Each function is assessed as shown in step two of Figure 4, and assembled into mission segment modules (step 3). The output is a computer printout (step 4).

BASIC PURPOSE OF TBLA

Simply stated, the basic purpose of the TBLA is to delineate, at a function or task level, the relative load experienced by the operator at a given time in the mission, and hence, determine how effective the control-display mechanization is likely to be.

OUTPUTS OF THE TBLA

A typical TBLA will provide the following data:

- Continuous or highly repetitive activities of an operator or operators.
- Discrete or intermittent activities of an operator or operators.
- Total elapsed mission time.
- Combined load (continuous and intermittent tasks).

In addition, the TBLA also contains the following parameters:

- The time interval during which a given category of information is presented on a primary display, e.g., flight director information.
- The time required by the operator to interpret the primary display information.
- The time interval during which a given category of information is presented on an auxiliary display.
- The time required by the operator to interpret the auxiliary display.
- The time required by the operator to control a given parameter.

While all phases of the Litton methodology are computerized, the TBLA program is the most sophisticated tool used in the analysis. Basically, the program takes stored data on each function and orders both pilot and copilot activities on a mission-oriented time base. For each function, the data contains the following information: (1) the mission time when the function is scheduled to appear; (2) the amount of time that would be required to accomplish the function; (3) the allowable delay that can be tolerated; and (4) the estimated load associated with each task or function as it is being accomplished. It should be noted that the data base contains different quantitative values for different mission segments and unique mission activities. The allowable delay feature introduced a priority scheme. Thus, a high-priority item will have a zero allowable delay while a low-priority item may have as much as several minutes. In addition, data is also compiled on each function for the amount of operator

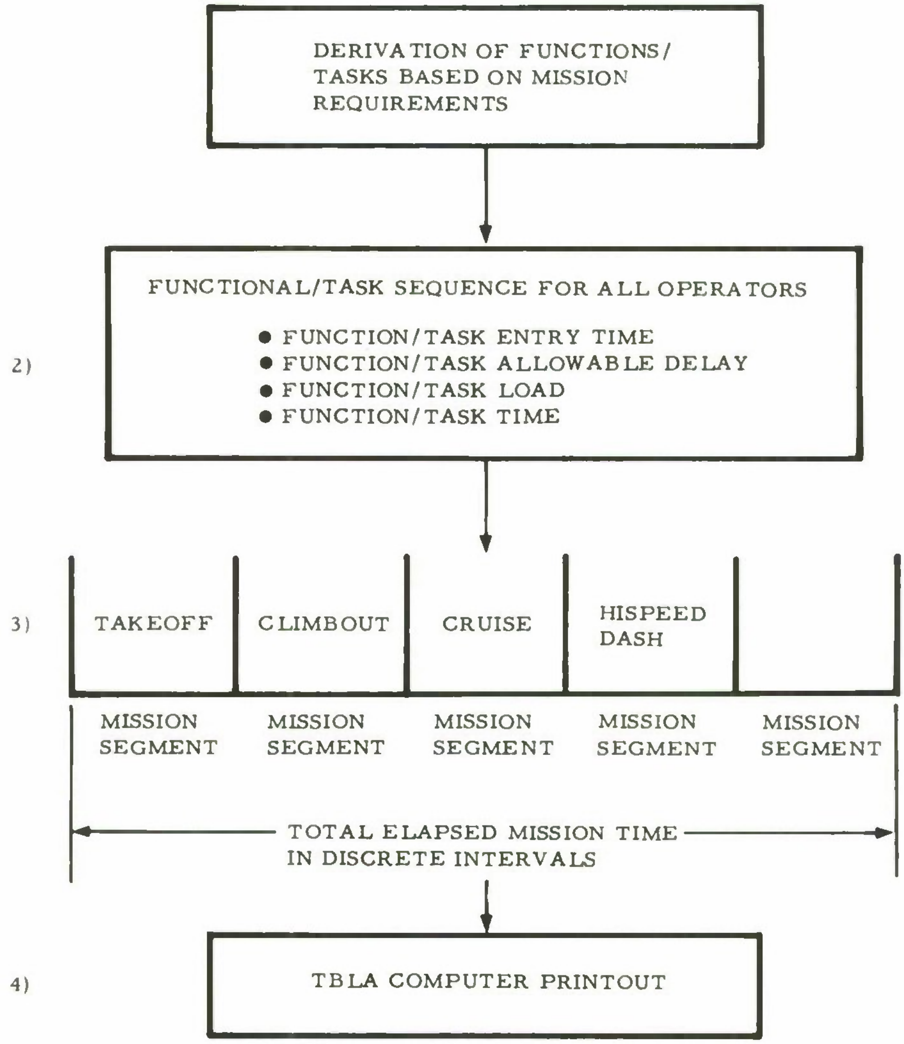

Figure 4. Overview of TBLA process.

load imposed while the task is being accomplished.

The computer program for the TBLA looks at the task to be initiated at a given time and the operator load present at that time, and on the basis of this information either delays the task by the allowable delay time or introduces that task immediately. This process is shown in Figure 5. For delayed tasks, the task is introduced after the allowable delay and an on-going task is delayed the "allowable delay" time, reintroduced, etc. The program thus adjusts the data in real time and keeps a running estimate of operator load conditions.

CONTINGENCY ANALYSIS

After the potential contingencies have been agreed upon, and the associated functions delineated along with the load, time, and allowable delay, the data are entered and the TBLA is run. Figure 6 is a logic diagram that illustrates how the computer handles the introduction of contingency actions. A basic rule of the TBLA is that any time a TBLA load reaches 100 percent, an overload condition exists. If the overload conditions exist for more than a short period of time (i.e., ten seconds), a potentially dangerous situation can be expected.

The analyst compares the TBLA without contingencies and with contingencies. It is possible to see how the computer adjusted task entry times to avoid operation overload in a contingency situation. This provides the analyst with an approach for similar juggling of tasks.

In summary, the TBLA program cycles through the selected mission imposing a given contingency at selected intervals throughout the entire mission. The computer printout is a simple listing of the times when an overload

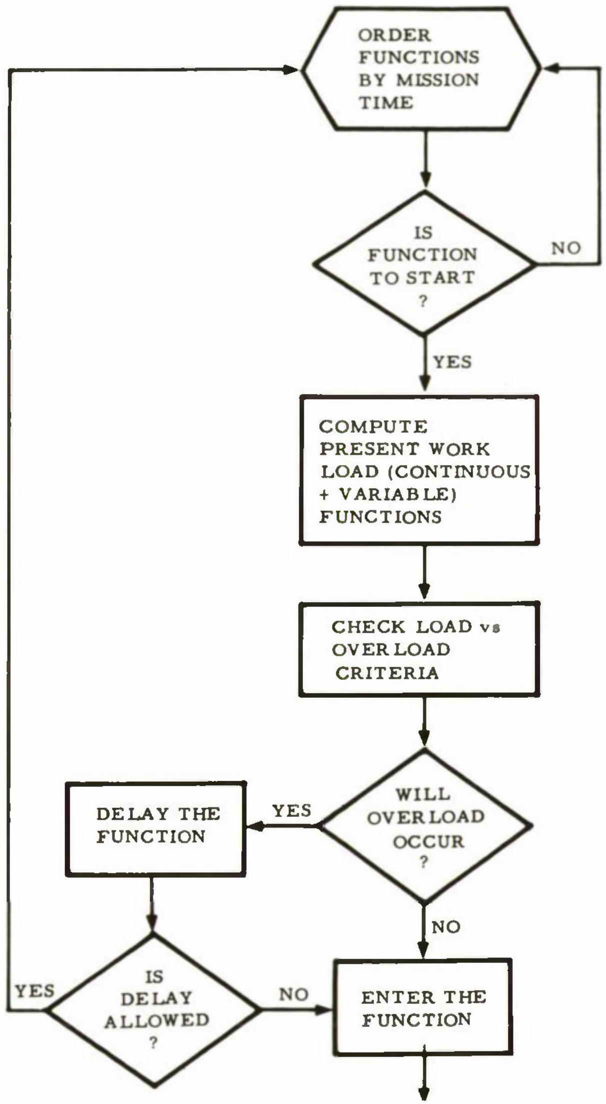

Figure 5. Logic diagram for the time-based load analysis.

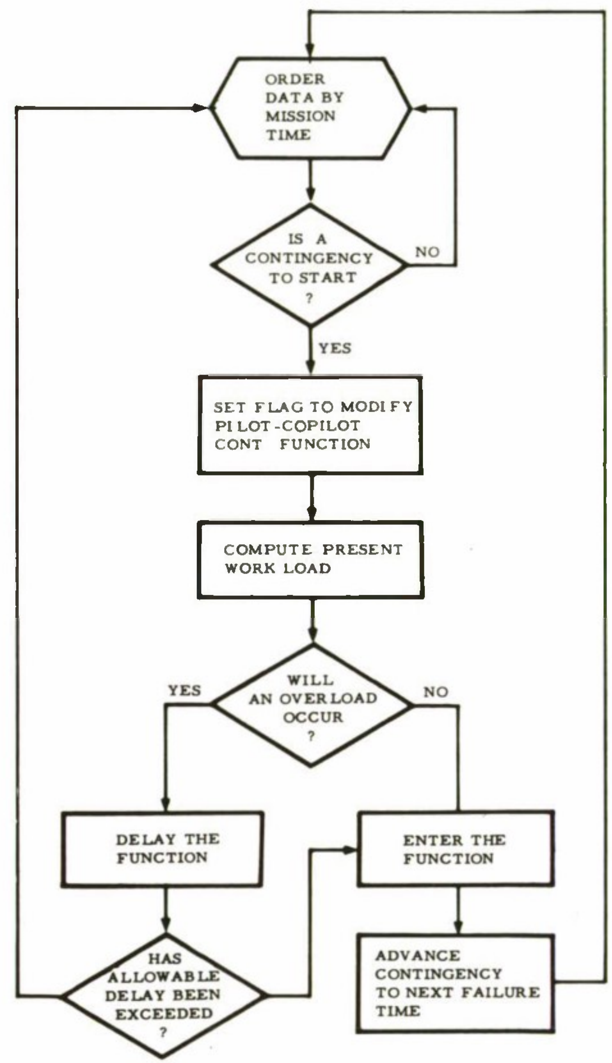

Figure 6. Logic diagram for determining the effect of a contingency occurring at any point in the mission.

existed. Subsequent computer printouts can then be requested just for the overload periods to identify any tasks that consistently result in an overload situation. The emphasis is on detecting operating procedures that can be reappraised for alternative mechanization approaches or in reallocating tasks if they appear unreasonable.

COMPUTER FORMAT OF THE TIME-BASED LOAD ANALYSIS

The TBLA format, as used in a recent Army program is shown in Figure 7. The continuous and repetitive functions are shown in the seven columns following the name of the function. These columns have x's presented vertically more or less continuously throughout the mission. For the pilot the first column will always be reserved for intercom, the second for monitor engine instruments, etc., as indicated.

The column reserved for intermittent tasks is also indicated adjacent to the continuous column. For the intermittent tasks, the time during which the function will be performed will be indicated by x's starting directly across from the function name and proceeding vertically for as long as the function is being performed. In other words, to identify those functions indicated by x's in the CONT. column, it is necessary to identify which of the six columns within the CONT. column contains the x. For the intermittent functions, the x's indicating start time show in the VAR. column.

The LOAD column for both the pilot and observer lists the load value numerically alongside the elapsed time column which is structured on a five second interval basis. The italicized heading (item No. 1) shown in Figure 7 is a function. The tasks associated with the function are designated with an asterisk.

NO.	PILOT FUNCTIONS	CONT.	VAR.	LOAD	TIME	LOAD	VAR.	CONT.	OBSERVER FUNCTIONS
	MONITOR AIRSPACE *CONTROL HDG* *CONTROL A/S* *CONTROL ALT* *CONTROL ATT* *MONITOR ENG INSTR* *INTERCOM* PILOT TASKS								*MONITOR AIRSPACE* *DET A/C PP* *INTERCOM* **SLEW SENSORS* **MONITOR D/NS* OBSERVER TASKS
C823		x	xx	36	3235	57	xx x	x x	
0824	*CHECK SLEW POSITION	x	x x	27	3240	17	xxxx		*CHECK SLEW POSITION
0825		xx	x	91	3245	64	xxxx	x x	*CHECK ALIGNMENT (LASER)
0826	*SELECT POLARITY	xx	xx	32	3250	29	xxxx		*CHECK POLARITY
0827	*SELECT DC RESTORE	x	xx	14	3255	68	xxxxx	x x	*SELECT DC RESTORE
0828		x	x	29	3260	30	xxx	x	
0829		x x		58	3265	65	x xxx	x x	*ADJUST DICPTER
0830		xx		21	3270	41	xxxxx		*ADJUST BORESIGHT ZERO
0831		x		25	3275	92	xxxxx	x x	
0832	*BALANCE PICTURE	x	x	10	3280	36	xxxxx		*OPTICS CHECK?
0833									*BALANCE PICTURE
0834	*SELECT SYMBOL	x x	xx	80	3285	89	xxxxx	x x	
0835		x x	xx	71	3290	59	xxxxx	x	
0836		x	x	24	3295	94	xxxxx	x x	
0837		x		11	3300	50	xxxxx		*VERIFY LASER ON
0838		xx		79	3305	89	xxxxxx	x x	*SETUP PRF
0839		xx		20	3310	54	xxxxxx		*SELECT PRF CODE
0840		x		10	3315	89	xxxxx	x x	
0841		x		25	3320	59	xxxxxx	x	*MONITOR OVERHEAT
0842		x x		58	3325	94	xxxxx	x x	

Figure 7. Time-based load analysis format.

CONCLUSIONS AND THE FUTURE

In conclusion, the major facets of the TBLA are summarized below. The TBLA:

- Provides assessment of operator/avionic system mechanization--short of simulation or actual run.
- Provides a diagnostic technique for assessing overall crew/system effectiveness.
- Isolates operator overload situations.
- Allows feedback into crew station layout for correction purposes.
- Puts the entire mission into an operating context.
- Identifies continuous and variable demands.
- Provides guidance on test and evaluation areas.
- Evaluates the impact of contingencies on operator performance.

FUTURE EXPANSIONS OF THE TBLA

A variety of refinements can be included for future expansion of the analysis. A logical group of parameters to extend the analytic value are summarized below:

- Using the cumulative fatigue factor--a relative appraisal of fatigue factor that occurs as a function of mission duration and load.
- Providing more than a two-operator flow to assess load of three or more operators working in concert.
- Providing an assessment of total task complexity. This would afford the analyst the opportunity to make a better judgment as to task reallocation if an overload occurs.

AREAS FOR FURTHER ANALYSIS

While the TBLA appears to be a valid analytic tool, it still can profit by improvement in the following areas.

TASK TIMES

Better data should be procured in the area of discrete task times. This data could be obtained by actual flight test data of the candidate aircraft system by measurement in the classical manner. However, the intent of this refinement would lie in obtaining very *specific* task times rather than generic task times. For example, if the manipulation of a specific sensor, under specific circumstances such as low level IFR, can be recorded, this would have much more analytic value than a generic value associated with a manipulation of a hand controller derived in a laboratory situation.

ALLOWABLE DELAY

In the area of allowable delay estimates, again empirical data on *how* long a task or function can be delayed without a degradation of performance and/or safety should be obtained. This could be accomplished by following the task sequences derived in the methodology (following the scenario) and measuring the shift in tasks, the actual task deletions, and in essence looking at the "real world" priorities that develop in flight. The relationship of allowable delay to operator load should also be studied. It would appear that a direct relationship exists between the amount of load and the allowable delay of a particular task across the total mission spectrum.

LOAD ESTIMATES

Perhaps the key area that needs refinement and more investigation is in the area of estimating operator load. The estimates used in the recent Army study TBLA were based on John Barnes' Information Transfer Studies in Helicopters. This analysis, which was conducted under mission conditions, measures the amount of operator use with respect to the instruments he is using to fly the aircraft.

It would be desirable to expand this type of study to include non-piloting tasks in a variety of aircraft systems. For example, more detailed use measurements are required for sensor operation, navigation, and communication tasks.

In particular, actual combat data would be very desirable, particularly as it relates to weapon delivery and flight control.

ACKNOWLEDGMENTS

The author would like to thank Dr. John V. Murphy of Litton Data Systems Division, who was instrumental in conceiving many of the original features of the TBLA, and Dean M. Pierce, System Applications programmer at Litton, without whose patience, insight, and expertise, the development of TBLA could not have occurred.

In addition, active support and encouragement of the analysis activities were provided by Mr. Brad Gurman and Mr. Willis Dworsak of USAECOM and Mr. James Hatcher of USAVSCOM.

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LED MEASUREMENTS

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Abstract: *This paper presents an overview of photometric measurement principles and describes the major problems associated with the photometric measurement of light emitting diodes (LEDs). The paper also describes an instrument that has been built to measure LED integrated illumination by photometric methods and a second instrument being built for LED measurement by both photometric and radiometric methods.*

Photometry deals with the summation of the integrated visible radiant light energy, as modified by the response of the average person's eye. Since scientists do not fully understand how the combination eye and brain works, it was necessary to make an educated guess as to the response of the eye of the average human to visible wavelengths. W. W. Coblantz and W. B. Emerson published a paper covering this subject in 1917. This paper shows the response of 125 observers to equal energy at each wavelength from 420-nm to 700-nm. From this plot, it can be seen that there are wide differences in response between observers at any given wavelength. However, all the observers show peak response in the green region of 540- to 560-nm and close to zero response at the blue end (400-nm) and red end (700-nm). This was the beginning of the so-called "average observer response curve," arbitrarily decided upon by the Optical Society of America in 1922, and revised by the International Commission of Illumination in 1931.

We need to know the average eye response to any given light source because if we are going to put numbers to photometric units, and two photometers are to give the same results, when reading the same source, then it was necessary to establish universally the average observer response curve.

In the case of the physical photometer, which uses a sensing element like a photo cell, photo tube, PM tube, etc., the response of the sensing element must be corrected with filters to match (as closely as possible) the ICI average-observer response. The photometer is then calibrated to a luminous standard so that it reads the integrated radiant energy of the source as modified by the response of the average observer's eye.

It should now be clear that the units used in photometric measurements can be looked upon as the integration of the absolute radiant energy values modified by the response of the average observer.

The term "absolute radiant energy" has been used. It is possible to break down the source of light into its various wavelengths and measure the energy at each wavelength. This is called a radiometric measurement, which does not involve the human eye response. Radiometric data can be converted to photometric data by mathematically multiplying them by the average observer's function.

The discovery of light-emitting diodes has led to their wide usage in the field of information displays. Presently available LED are made from gallium arsenide phosphide and gallium phosphide, having peak emissive wavelengths of from 550 (green) to 690 nanometers (red) and bandwidths of from 50 to 100 nanometers. Their brightness levels can vary from 80 to 2500 fL. Epoxy treatments can cause lens effects or diffusion so that the luminous intensity can vary with angle off axis. Because of these peculiar characteristics of LED, their measurements as to how the eye sees them must be carefully studied and standard methods of measurement must be established.

Measurements of the physical properties of light and light sources can be described in the same terms as any other form of electromagnetic energy. Such measurements are commonly called radiometric measurements.

Measurements of the psychophysical attributes of the electromagnetic radiation we call light, are made in terms of units, other than these radiometric units. Those attributes that relate to luminosity (sometimes called visibility) of light and light sources, are called photometric quantities, and the measurement of these aspects is the subject of photometry.

The engineer who is starting to apply LED and other optoelectronic devices to perform useful tasks, will find the subject of photometry to be a confused mass of strange units, confusing names of photometric quantities and general disagreement as to what the

important requirements are for his application.

The photometric quantities are related to corresponding radiometric quantities by the CIE Standard Luminosity Function, which we may refer to as the standard eyeball. We can think of the luminosity function as the transfer function of a filter which matches the behavior of the average human eye. The eye responds to the rate at which radiant energy falls on the retina, that is, the radiant flux density expressed as Watts/m^2. The corresponding photometric quantity is Lumens/m^2. The Lumen is the unit of luminous flux. Thus, the total luminous flux emitted by a light source in all directions is measured in Lumens. If we treat the source as a point, we can divide the space around the source into elements of solid angle and inquire as to the luminous flux contained in each element of solid angle. The resulting quantity is Lumens/Steradian and is called luminous intensity. The unit of luminous intensity is called the candela, sometimes called the candle or candle-power.

A steradian is a specific type of solid angle. It is important to understand the steradian.

$$\Omega \text{ steradians} = \frac{\text{area } (ft^2)}{\text{radius } (ft^2)}$$

Assume a cone whose apex is at the center of a sphere with a radius "R." It subtends a certain position of the total sphere's area. In the case of a steradian, the subtended circular area in square feet equals the sphere radius (in feet) squared.

Thus, if the total area of a sphere equals $4\pi R^2$ and the radius is R, the area of a sphere of one foot radius totals 4π (12.556) steradians. From this you can see that the solid (cone) angle of a steradian is always the same, no matter what the radius of the sphere.

For an extended radiating surface (LED) each element of area contributes to the luminous intensity of the source in any given direction. The luminous intensity contributions in the given direction, divided by the projected area of the surface element in that direction is called luminance of the source (in that direction). The quantity is sometimes called photometric brightness or simply brightness.

The measurements of Luminous Flux (Lumen Output), Luminous Intensity (candlepower) and Luminance (photometric brightness) are the three basic photometric tests which can be used to appraise the light-producing qualities of LED.

For all practical lighting conditions, all LED devices currently available and all viewing distances, the light emitting areas are large enough to be seen as extended sources by the eye.

For convenience, assume an area surface with a luminance in all directions of one candle per unit area. The luminance of an extended source differs from that of a point source in that it takes cognizance of the emitting area. By definition, the luminance (brightness) of an extended source is the luminous intensity per unit per projected area of the emitting source. Since luminance, like intensity, is a function of the direction being considered, projected area rather than actual area is used, the projection being on a plane normal to the direction considered.

Because of the highly directional properties of LED, the direction lending itself to best definition is normal to the emitting plane.

The method described here measures the horizontal candlepower of the source and by means of the area this is converted to brightness. This amounts to treating the light source as though it were a point source, then computing the brightness that a surface of its emitting area must have had in order to give the candlepower reading. This then reads the average brightness of the emitting source.

If the source to be read is multi-element, it then may be measured, element at a time or with all elements lit. The complexity makes little difference as long as the apparent emitting area is known for the unit to be measured.

The source to be measured is placed at a distance of precisely one foot so that the reading obtained in footcandles is also the horizontal candlepower.

The candlepower of a source of light is its luminous intensity expressed in candelas. The luminance (brightness) of a source is its luminous intensity (candlepower in candelas) in a given direction per unit of projected area of the surface as viewed from that direction. Since the measurement is defined for the normal direction, the projected area is equal to the actual area. Therefore,

$$\text{Brightness (Footlamberts)} = \text{CP} \times \frac{\pi}{\text{area}}$$

The first instrument built for specific measurement of LED integrated illumination is described as follows: considering the light output levels, a detector intercept angle of four to five degrees, centered with respect to an axis coincident to LED centerline axis was used to define the average candlepower of the LED. A baffle is mounted in a tube at a distance and hole size which is determined by the

solid angle of acceptance. The tube in front of the sensor is one foot long and adjustable for length for varying sizes of LED. A PMT tube is used as a sensor. The PMT has a diffuser and correction filter to photopic match. The instrument is calibrated for footcandles on a photobench. Since the distance from the sensor to the LED is equal to one foot, then the footcandles measured represent the same value of candlepower.

PMT tubes are best suited as detectors (because of their high sensitivity) for the measurement of luminous intensity. To improve the spectral response of the detector, a correction filter is selected to have the best match to the photopic in the region of 500-700 nanometers. The error due to the deficiency of the response curve can become intolerably large since the calibration standard must of necessity be an incandescent lamp. The two are widely different in spectral distribution. In this case a correction must be calculated as per methods suggested in the paper by G. Fiat of Photo Research and George Hardesty and Tom Twist in a government report. This also would involve measuring the spectral distribution of the LED. This can be done with a fast scan system and results can be computerized, which automatically corrects the measurements. To get around having to measure the spectral distribution of the LED we have built a second instrument with several filter selections to match the photopic curve in several steps: 500-700, 570-630, 630-690, 670-730, and 400-750 nm. These steps are overlapping so that by shifting from one to another the peak output can be found. A correction is determined for each step since the positions are caliorated against our incandescent lamp.

Another instrument is being built to measure LED by both photometric and radiometric methods. The probes will be calibrated photometrically in terms of luminous intensity, and also in radiometric units of Watts/Steradian. These probes will measure over 4°, 13°, and 2π steradians for both chip type and single LED.

At a meeting of the Jedec JC-23 committee, it was generally agreed that luminance was not adequate as a single measure and that luminous intensity (candelas) was preferable. It was agreed that measurement of total luminous intensity (luminous intensity into 4π steradians) was best for monitoring output but generally does not correlate well with the viewer's sensation of brightness; also it is somewhat difficult to measure because of the need for integrating sphere. Consensus followed that of the five following parameters, the first three were most important and should always be specified; the fourth and fifth parameters would provide useful information and should be supplied when feasible.

1. Luminous intensity (or total lumen output) into forward hemisphere (2π steradians).

2. Luminous intensity into small angle (less than five degrees) on axis.

3. Polar coordinate plot of small angle luminous-intensity (goniophotometric plot of luminous-intensity).

4. Apparent size of light emitting area.

5. Luminance, on axis.

A REAL-WORLD SITUATION DISPLAY FOR ALL WEATHER LANDING

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Abstract: *This paper describes a flight data display for use in aircraft approach and landing under all conditions of visibility from CAVU to zero-zero. It is particularly notable that the display does not require a flight director. The display was developed by application of the building block concept and can be operationally implemented in the same manner. In its simplest form it provides airborne self-contained glidepath guidance for use in visual flight conditions and in its most sophisticated form it provides total information for manual landing, or for monitoring automatic landing, and roll-out during zero visibility conditions. The basic concept is derived from the authors' observation that pilots have no difficulty landing aircraft by reference to the original head-up display, i.e., the real world as seen through the windshield in clear weather. The display advocated is extremely simple and uncluttered. Essentially a situation display, it employs a minimum of computer input. Being usable in all conditions of visibility, the display would lead to the development of pilot confidence and competence and drastically reduce training time. The authors contend that head-up display of symbology similar to that described is urgently required for see-to-land approaches and will be essential for pilot acceptance of automatic landings in actual non-visual conditions.*

The authors of this paper sincerely appreciate this opportunity to present our views on the subject of flight data display. We are neither inventors nor designers. Two of us are airline pilots. The third is an aeronautical engineer. We venture to speak on the basis of long experience as users of flight instruments and because of the unique opportunities we have enjoyed as members of the All Weather Flying Committee of the Air Line Pilots Association. It has been our privilege to consult with leading authorities throughout the western world--engineers, scientists, pilots, and government officials--specializing in various aspects of the all weather landing problem.

We have flown most of the displays presently available and have examined a number of others currently in the design stage. We have participated in the investigation and analysis of a long and continuing series of accidents in which airline aircraft have struck ground objects or crashed short of the runway; and we have spent a great deal of time studying and debating all weather landing criteria developed by national and international representatives of government and industry.

This activity has led us to a number of conclusions, three of which are the premises of this paper:

Conclusion #1. There is a clear and present operational requirement for vertical guidance (at least pitch and glidepath) displayed in such manner and location that it can and will be observed during the visual segment of see-to-land approaches.

Conclusion #2. The flight data display for monitoring automatic landings in non-visual conditions will necessarily provide a consistent manual landing capability equivalent to that attainable with the automatic system.

Conclusion #3. The *best* way to satisfy the vertical guidance requirement for the visual phase of see-to-land approaches and the *only* practical way to assure an adequate capability for manual landing in non-visual conditions is through head-up display of appropriate flight data.

In our opinion, further healthy advances toward the all weather landing goal will require head-up display of localizer and glideslope situation data, stabilized in all axes, superimposed upon the real world runway and supplemented with symbolic presentation of essential auxiliary data. We advocate a building block concept in which the head-up display would be used for all landings throughout the entire spectrum of visibility conditions--clear day through zero-zero night.

Since the beginning of commercial jet operations some 13 years ago, nearly 20% of the major accidents have occurred during night approaches over unlighted terrain or water toward well-lighted cities and airports. In all cases, meteorological conditions were

such that the flight crew could have employed visual reference to light patterns on the ground. The record of such accidents continues to expand and the requirement for vertical guidance in the *external* visual field becomes increasingly evident.

To properly comprehend the night visual approach problem, it is necessary to understand that aspect of the external visual scene by which pilots judge whether they are on, or above, or below the desired glidepath. Figure 1 depicts the pilot's forward view at various points along a common glidepath. The shaded rectangles on the runway identify the pilot's aiming point. Note the vertical distance between the aiming point and the horizon. This distance, which some call the *H-distance*, is the only dimension in the external visual scene that remains constant as the aircraft descends along a constant glidepath. As depicted in Figure 2, if the aircraft deviates upward from the desired glidepath, the H-distance increases. Deviation below glidepath reduces the H-distance.

In jet transport aircraft, visual approaches are normally flown at a glidepath angle of approximately three degrees. A shallower approach can result in too little clearance over obstacles--a problem which is most critical with large, long-bodied aircraft whose landing gear hang far below and behind the pilot's eye. But three degrees is a very small angle, difficult to estimate. The H-distance for a three-degree glidepath is about equal to the width of a pilot's thumb held at arm's length. Dangerous deviations below the desired glidepath can escape immediate detection by the flight crew. When such deviation is associated with windshear, the hazard is compounded; but probably the greatest risk arises when terrain features and ground lighting patterns combine to portray the horizon high above the level at which it would be seen in flat terrain.

The Boeing Company conducted research in a simulator to test the effect produced when the H-distance is exaggerated by city lights on hills behind an airport. The

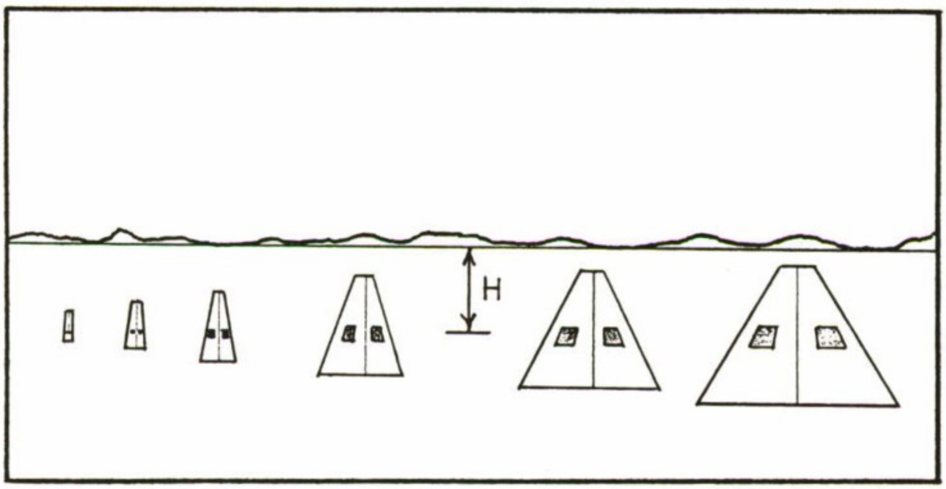

Figure 1. Pilot's forward view at various points along a common glidepath.

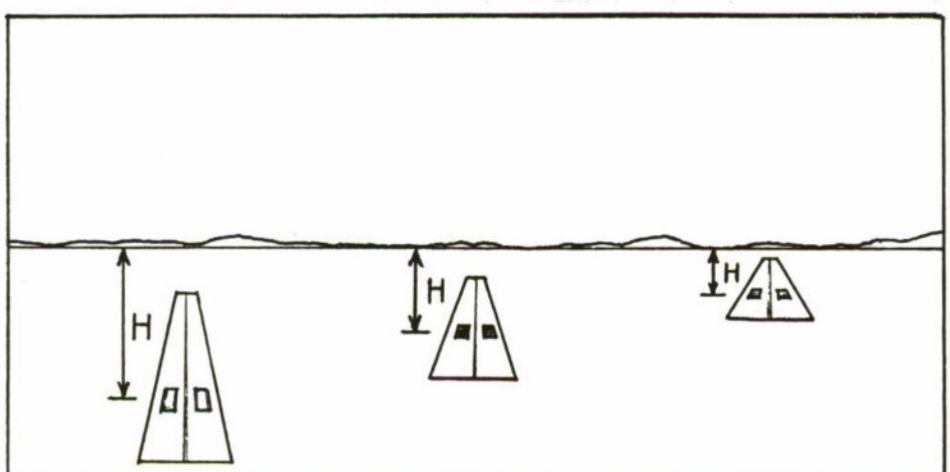

Figure 2. Variations in H-distance as a result of deviations from desired glidepath.

apparent horizon was elevated sufficiently to give the pilot the illusion of being on a three-degree glidepath when the aircraft was actually at runway elevation. Subject pilots tended to descend to the elevation of the runway while still some four miles short of the airport. One pilot descended 2,500 feet below the airport level.

Figure 3 is our attempt to pictorialize this phenomenon. The dashed line represents the true horizontal level. The runway is long and upslope and the aircraft, though still approximately four miles short of the airport, has already descended to the approximate elevation of the runway.

The vast majority of approach accidents occur when descent is made without benefit of electronic glidepath guidance. For this reason ALPA favors installation of ILS for all runways, but the accident record indicates that *visual* glideslope guidance is required even when electronic glidepath guidance is provided.

The VASI system was designed to provide such guidance. We strongly advocate its installation on every runway; nevertheless, we recognize that the vertical guidance provided by VASI is far from ideal. It alerts the pilot to deviation from the desired glidepath but provides very little practical information regarding the extent or rate of deviation. Lack of this data, particularly when the deviation is caused by windshear, can be extremely serious. In our opinion, head-up display of vertical gyro and flight path angle data is highly preferable to VASI. The VFR HUD or Airborne VASI, as it is sometimes called, provides excellent glidepath data--not only direction of deviation but also extent and rate. Furthermore, it has the potential for presentation of other desirable visual approach data--particularly airspeed or angle of attack. It is the ideal basic building block for the ultimate IFR display.

This leads us to a discussion of another cause of visual landing accidents. Approaches are now authorized in conditions of very low visibility and pilots are encouraged to continue descent by external visual reference if approach lights are in view at decision height. It is not intended, of course, that reference to head-down instruments be discontinued when visual reference to approach lights has been established; nevertheless, such is frequently the effect because the pilot is so burdened by the task of attempting to fly by reference to approach lights that he has little or no time for scanning the head-down instrument panel.

But the approach light system is not designed to provide, and does not provide, vertical guidance. A segment of approach lights viewed through fog, especially at night or when the approach is made over water, is at best a treacherous indicator of pitch, glidepath, altitude, or flight path angle. Perhaps this can best be illustrated by an episode which, though hypothetical, is based upon a phenomenon which appears to be central to a series of accidents in recent years.

A routine ILS approach was conducted for landing on a fogbound runway. The pilot was flying or monitoring the autopilot by reference to panel-mounted instruments. Just as the aircraft arrived at decision height, 200 feet above runway elevation, the copilot announced that approach lights were in view; whereupon the pilot lifted his eyes from the head-down instrument panel to scan the external scene. As has been confirmed by USAF research in actual low visibility approach conditions, it takes four to five seconds to complete this transition. During this period the pilot controlled his aircraft in pitch by

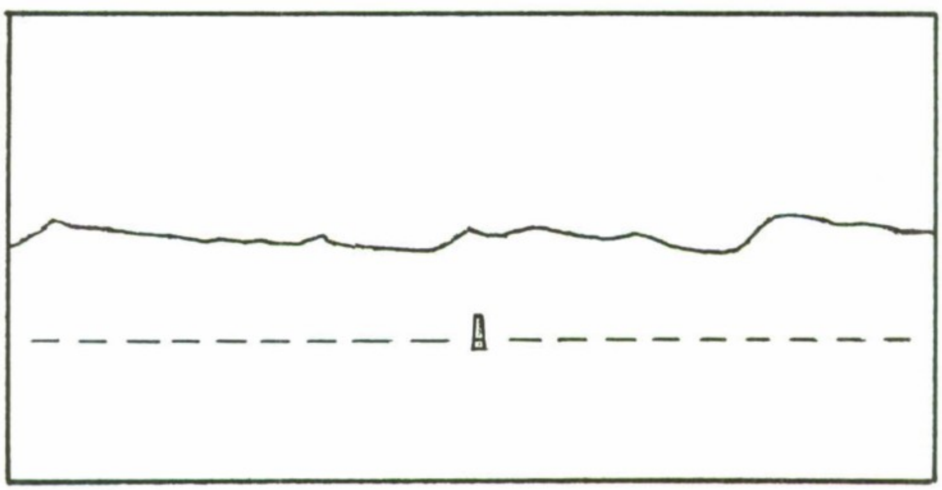

Figure 3. Visual field during landing approach (see text).

keeping the far end of the visible segment of approach lights in that section of the windshield where he was accustomed to seeing the aiming point, unaware that in so doing he had eased the windowsill down approximately an inch and a half, which in turn had caused the descent rate to increase to approximately 25 feet per second.

Four seconds after arriving at decision height, the pilot observed a rapid growth of all dimensions in the approach light segment. Even more alarming, the far end of the segment was moving rapidly toward the top of his windshield. At this instant the wheels of the aircraft were approximately 90 feet above the approach lights and were descending 25 feet each second. Tests have shown that human reaction time varies upward from a minimum of approximately one-half second. This pilot began pulling on the control wheel when the landing gear was approximately three seconds above the approach lights. We will allow you to finish the story; but we believe you will agree that head-up display of pitch data would help avoid recurrences. The value of including localizer and glideslope data in such a display also seems self-evident.

The value of head-up display for see-to-land operations is rapidly gaining recognition. What seems to be less obvious is that only HUD, used routinely on *visual* landings, can provide the necessary means for building pilot confidence and competence in the use of the display by which he will be expected to monitor or manually perform landings in *non-visual* conditions. If the monitor display is mounted on the head-down panel, it will not be observed during the critical stages of visual landings and pilots will not develop the confidence required for relying on the automatic system in actual non-visual landing conditions.

There are those who would relegate the human pilot to a break-glass-in-case-of-emergency role for the non-visual landing. With the landing controlled by a triumvirate of "voting" computers, the human pilot would be given a flight data display of sufficient quality for recognizing a breakdown in the automatic system and for making a missed approach, but not adequate for landing by manual control. Those who advocate this arrangement apparently think of manual control in terms of flight directors and computers. They therefore believe that the man-machine interface for reliably safe manual landing in non-visual conditions would necessarily be at least as complex as a full failure-survival automatic system.

We believe that airline pilots--at least in the United States--will firmly reject the monitor-only role precisely because a pilot cannot adequately monitor another pilot, whether man or machine, unless he is provided data adequate to permit him to match the capability of the pilot being monitored. Is the aircraft properly adhering to the localizer and glideslope? Maintaining the desired airspeed? Flaring properly? Decrabbing? Steering down the centerline? Decelerating adequately? If the display does not provide this information in a manner suitable for manual performance, in our opinion it is not adequate for the monitoring function.

In taking this position, we do not intend to imply that a trio of computers directing a highly-refined automatic system would not be highly preferable to a single computer directing a frequently tired and overloaded human pilot. Fortunately this is not the only choice. We strongly support the use of automatic equipment for the non-visual landing; and we agree with those who oppose using a flight director computer to monitor the autoland system. For monitoring the non-visual landing we advocate a situation display of raw guidance data, focused at infinity and projected in the windshield area so that the display symbols would overlie and complement their real world counterparts. Given a display of this nature, supplemented by a minimum of essential ancillary data, we believe the human pilot can demonstrate the same degree of repeatable performance attainable with an automatic system. Witness his ability to land by reference to the original head-up display--the real world as seen through the windshield on a clear day.

The basic building block of the symbology we advocate is depicted in Figure 4. It consists of an artificial horizon and relative heading indicator. All component markings of this basic element are fixed in relation to the horizon and are gyroscopically stabilized in pitch, roll, and yaw. The pitch marks are centered on a perpendicular to the horizon. Their lateral position conforms to the magnetic heading of the runway which is preset by the pilot. The triangle on the horizon line represents the runway heading. The small marks suspended from the horizon line denote five degree intervals left and right of the runway heading. Starting at the top, the pitch marks denote 15, 10, and 5 degrees above horizon. The circle and the X are respectively three and six degrees below horizon. In the picture, the aircraft is aligned with the runway centerline, as shown by the fact that the centerline is perpendicular to the horizon and passes through the circle and the X. The aircraft heading is parallel to the runway heading, as shown by the fact that the runway heading index and pitch marks are in the center of the display. Finally, the aircraft is directly on the three-degree glidepath to the aiming point on the runway, as shown by the fact that the three-degree circle superimposes the aiming point.

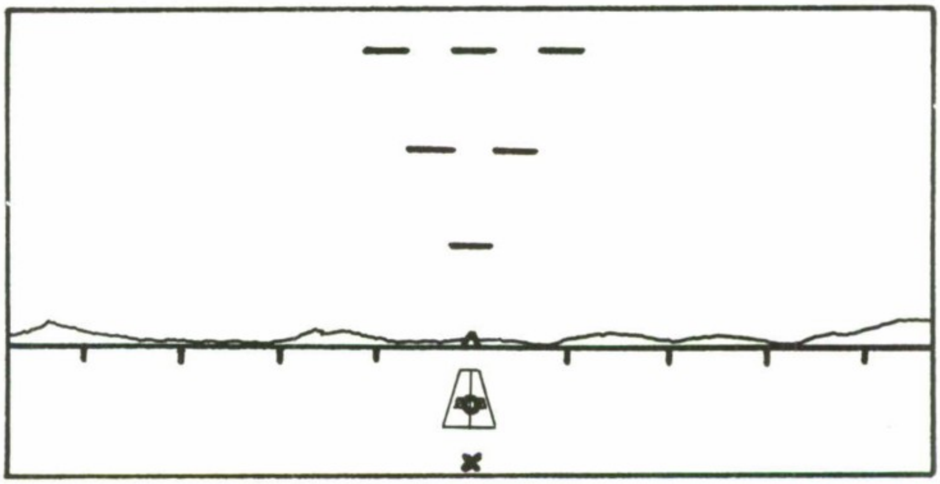

Figure 4. Basic building block of symbology consisting of artificial horizon and relative heading indicator.

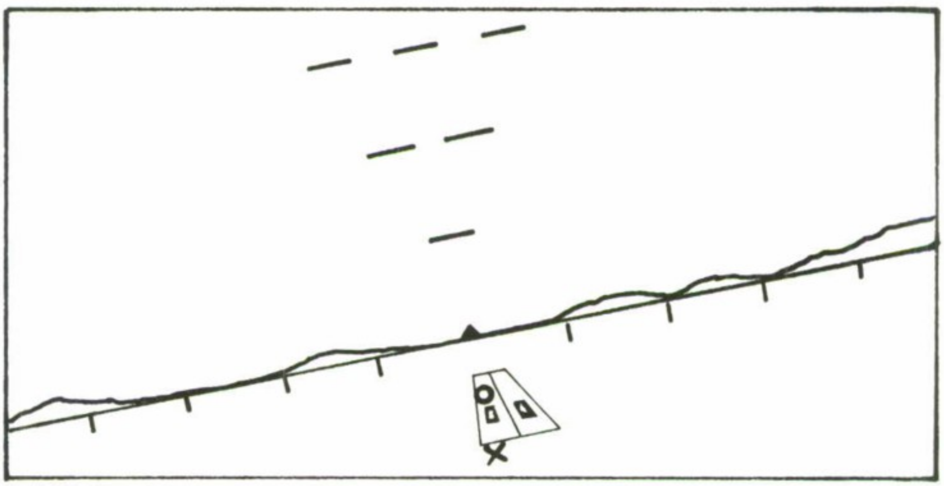

Figure 5. Basic building block of symbology with aircraft displaced left of runway centerline.

In Figure 5, the aircraft is displaced left of the runway centerline, as shown by the circle being to the left of the centerline. The aircraft is in a bank to the right but has not yet departed from the runway heading, as shown by the fact that the runway heading index is still in the center of the display. The aircraft is displaced above the desired three-degree glidepath, as shown by the circle being above the aiming point on the runway. To correct for displacement from the runway centerline, the pilot must turn to his right--as he is doing. To correct for displacement above the desired glidepath, he will need to increase his rate of descent. The circle is flown to the runway centerline and to the aiming point in the same manner in which pilots have learned to fly a conventional ILS crosspointer.

In Figure 6, the aircraft has completed the correcting turn and is heading to the right of the runway heading as shown by the center of the display being offset to the right of the runway heading index. The aircraft has pitched down as shown by the fact that the horizon and pitch marks have moved upward in the display. As a result of the correcting turn and pitch adjustment, the aircraft has nearly corrected its displacement from both centerline and glidepath.

Neither an artificial horizon nor a heading display is really complete without a symbol to represent the aircraft. In Figure 7, such a symbol is added. Patterned after the aircraft symbol in a conventional artificial horizon instrument, it conforms to the behavior of the actual aircraft in all axes--pitch, roll, and yaw. In pitch, however, it represents the velocity vector or flight path angle of the aircraft. In Figure 7, the

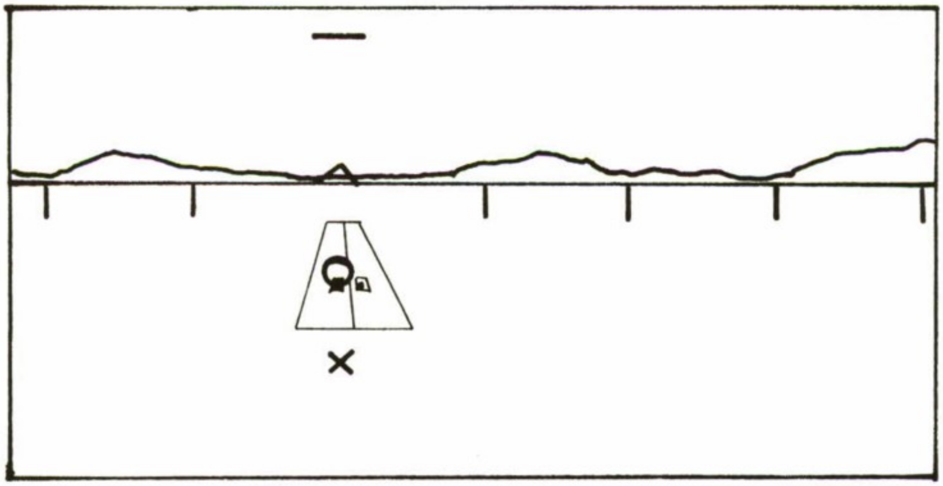

Figure 6. Basic building block showing aircraft after having completed correcting turn.

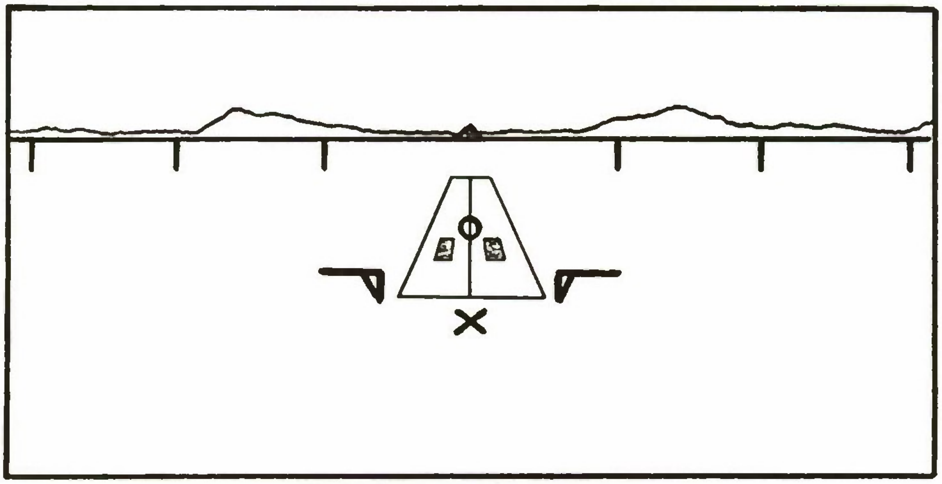

Figure 7. Basic building block with aircraft symbol added.

aircraft is descending at a flight path angle of approximately four or five degrees to correct for a slight displacement above the desired three-degree glidepath.

In Figure 8, the aircraft is on the desired three-degree glidepath and is descending at a flight path angle of three degrees. The aircraft has deviated slightly to the right of the runway centerline and is turning to the left to compensate. The present heading is approximately five degrees left of the runway heading. Note that a slow-fast or angle-of-attack meter has been added to each wing tip. The airspeed is five knots fast; or, if the indication represents angle-of-attack, it is one degree low.

In Figure 9, localizer and glideslope data have been added. The localizer is represented by the centerline of the tripod symbol suspended from the runway heading index on the horizon. It swings from that point in pendulum fashion depending on aircraft deviation from the runway localizer centerline. The aircraft is directly on the runway localizer centerline when the centerline of the tripod symbol is superimposed by the circle. The aircraft is shown in Figure 9 as being slightly left of centerline. The glideslope is represented by the parallel horizontal lines situated slightly below the circle. The aircraft is slightly above glideslope. The velocity vector, or aircraft symbol, is below and to the right of the circle; this should bring the aircraft back to both glideslope and localizer centerline. The slow-fast pointers indicate that the airspeed is ten knots slow. The rising mask at the bottom of the display represents radio altitude. When it touches the bottom of the heading marks attached to the horizon line, the wheels of the aircraft will be at zero altitude.

In Figure 10, the radio altitude mask has reached the wheels of the aircraft symbol.

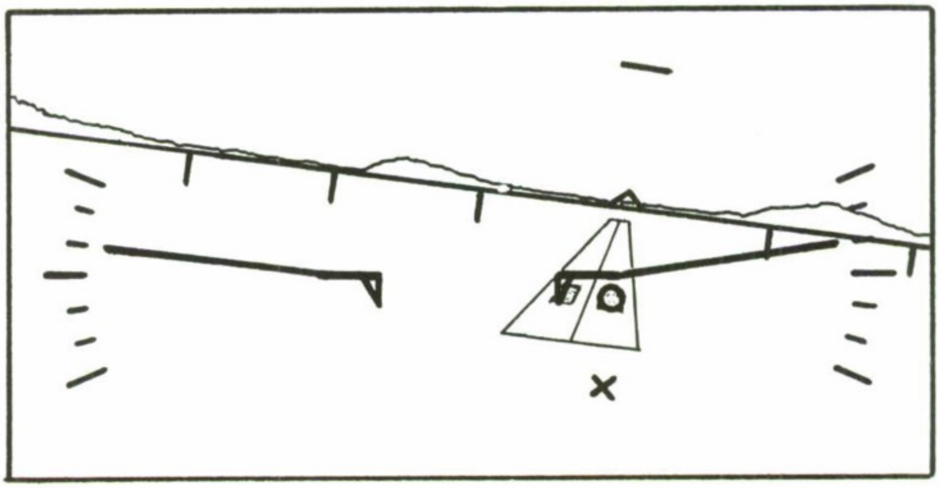

Figure 8. Basic building block showing aircraft on desired three-degree glidepath and descending at a flight path angle of three degrees.

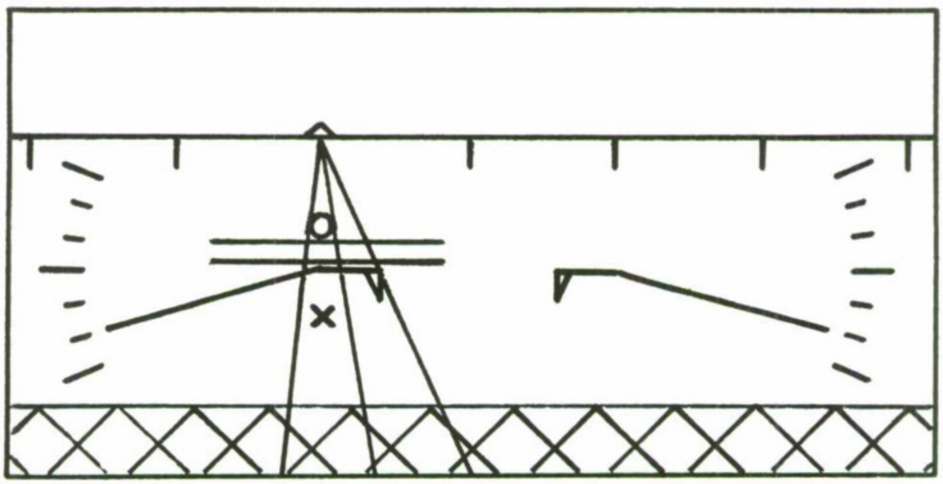

Figure 9. Basic building block with localizer and glideslope data added.

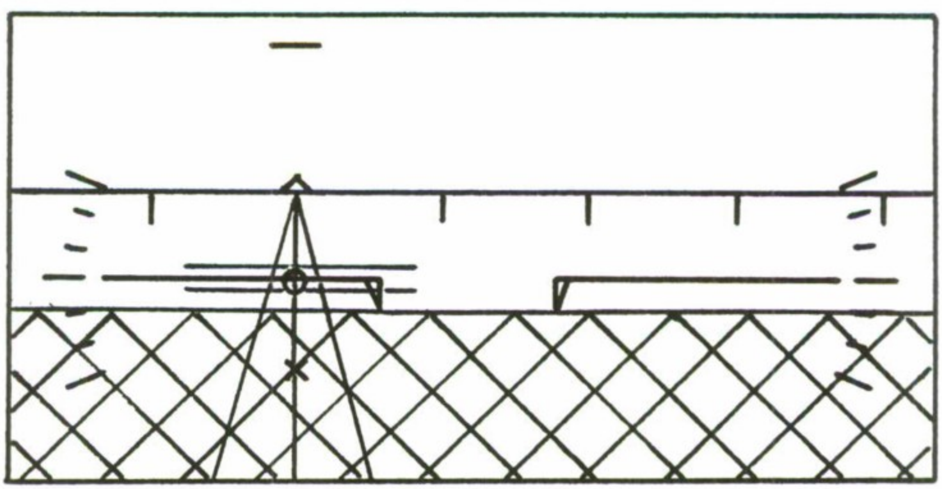

Figure 10. Basic building block with radio altitude mask having reached the wheels of the aircraft symbol.

The pilot should now begin his landing flare, elevating the aircraft symbol to match the rise of the radio altitude mask until the wings of the aircraft symbol touch the bottom of the heading marks. This will result in landing at a flight path angle of one degree with a descent rate of approximately three feet per second.

Coincident with flare initiation, the pilot may wish to de-crab. This will require rudder action, swinging the aircraft symbol to the runway heading index. In Figure 11, flare and de-crab are both completed and the aircraft, with its upwind wing slightly depressed, has very nearly reached the runway surface.

In Figure 12, the aircraft is on the ground. A scissor-switch on the landing gear has erased the radio altitude mask. The pilot is steering by keeping the aircraft symbol centered on the runway heading index and by keeping the circle on the localizer centerline. Notice that the wingtips are deflected upward. This signifies that a computer comparison of velocity, deceleration, and remaining runway length indicates that the aircraft will not stop on the runway unless braking action is increased.

In Figure 13, the pilot is conducting a missed approach. The aircraft is climbing at an angle of approximately seven degrees above the horizon and is heading approximately five degrees right of the runway heading.

The basic concepts involved in this display are, of course, neither new nor original. The idea of using them in a head-up display seems to have originated in both Australia and in the United States more than 15 years ago.

Two years ago, a somewhat elementary version of the display was tested at our request in an informal program in a NASA simulator at

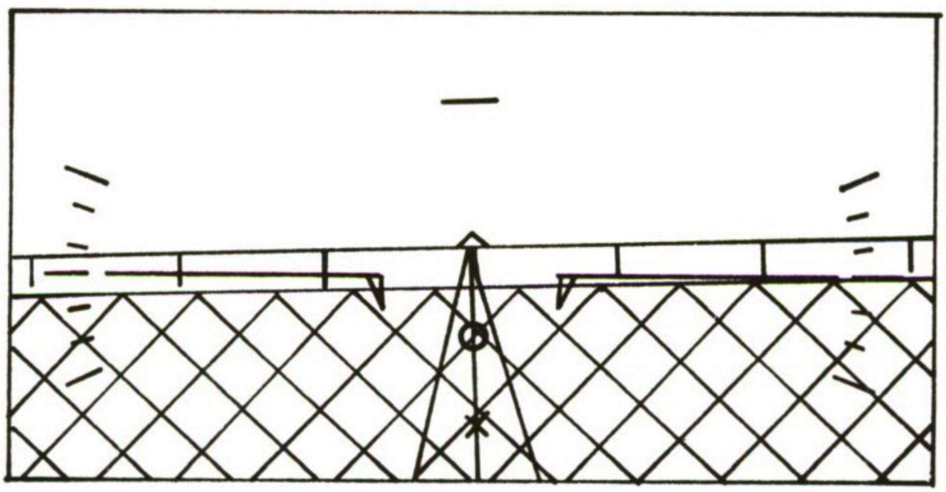

Figure 11. Basic building block showing flare and de-crab completed.

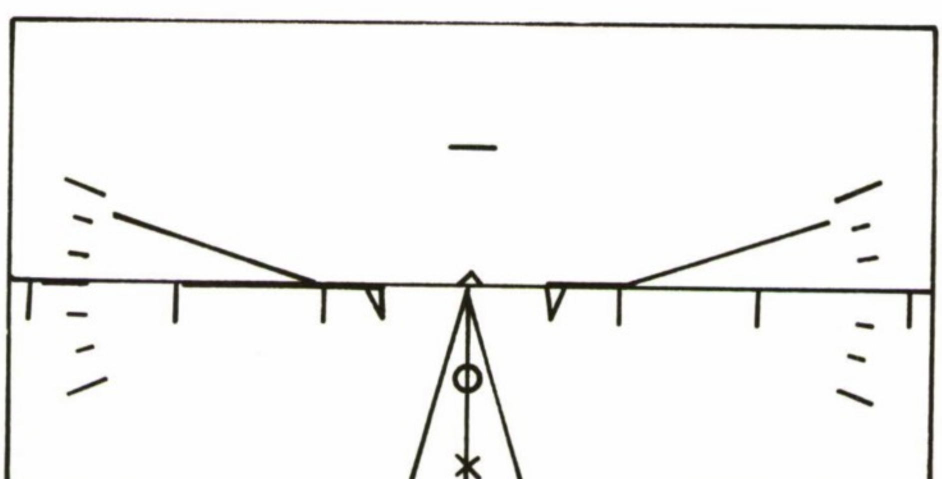

Figure 12. Basic building block showing aircraft on the ground.

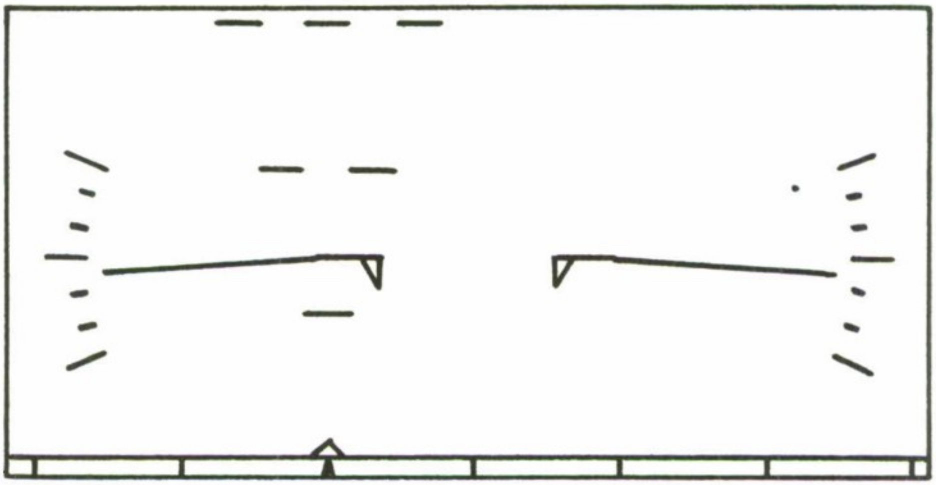

Figure 13. Basic building block showing pilot conducting a missed approach.

the Ames Research Center. As part of that informal program, one pilot who had made only one previous approach using the display made a run with the simulated visual range set at 1,200 feet. Without notifying him, a tail-wind shear was introduced, starting at an altitude of 400 feet on the glideslope and increasing steadily to 30 knots at 200 feet. On the same run, at the 300-foot altitude, a 20-knot crosswind component was abruptly added. Despite these complications and using only the raw ILS displacement data, the pilot remained on the glideslope and was fully re-established on the localizer with the proper crab angle and flight path angle when the runway came into view at approximately 80 feet.

The results of the informal program showed that raw ILS displacement information presented in this manner received greater pilot acceptance and could be flown with more accuracy than a conventional flight director. It was concluded that the display has great potential and warrants further investigation. Recently, we have been notified that the Ames Research Center has, at least tentatively, decided to establish a formal NASA program to conduct such investigation.

ELECTROLUMINESCENCE: STATE OF THE ART

MR. ROBERT DEMUTH
GRIMES MANUFACTURING COMPANY

Abstract: *This paper reviews the state of the art of electroluminescent panels. It describes the construction of electroluminescent lamps and discusses the physical parameters that are important in the design of an electroluminescent panel. A series of graphs displays the photometric characteristics of existing lamps and panels. Both color and intensity characteristics are reviewed.*

INTRODUCTION

Since the phenomenon of electroluminescence was discovered in 1936, enthusiasm for its practical application has spread into many fields of lighting and scores of papers have been written on the subject. However, certain characteristics of the lamp have prevented its widespread application. The tremendous potential of this lamp is realized by many designers. Continued improvements in lamp design and fabrication techniques prove that suitable applications are imminent.

This paper is restricted to a discussion of EL lamps as applied to aircraft control panels.

TECHNICAL DISCUSSION

The general term electroluminescence is used to cover various emission effects that can occur when certain phosphors are subjected to an electric field. The action of electric fields upon crystals embedded in an insulator was first reported in 1920 by Gudden and Pohl who pointed out a momentary afterglow from a phosphor previously irradiated by ultraviolet radiation. However, the sustained emission of light by a phosphor powder embedded in an insulator is associated with Destriau back in 1936.

Electroluminescence involves the direct conversion of electrical energy into light without recourse to any intermediate energy form such as heat, whereas the emission from incandescent bodies is determined by the temperature alone. The "cold" emission from an EL substance depends on its chemical and physical construction. Since the energy conversion cannot be 100 percent efficient, electroluminescent light sources do in fact heat up during normal operation depending on applied voltage and frequency. They remain cold sources, however, in the sense that no part of their emitting surface even approaches the temperature range of incandescence as the emitted radiation might suggest.

Intrinsic electroluminescence, the Destriau effect, covers light emission by suitable phosphor powders embedded in an insulator and subjected only to the action of an alternating field. The light emitted with the alternating field is not continuous but flickers with twice the frequency of the applied voltage. When an EL cell is subjected to a direct potential, only a flash of light occurs when the potential is applied and another flash when it is removed.

GENERAL CONSTRUCTION OF EL LAMPS

An EL lamp is simple enough in physical construction. It merely consists of a layer of properly prepared phosphor sandwiched between two electrodes (one of which is translucent to allow the light to escape) encapsulated between two pieces of plastic. Two leads are extended from the electrodes in order to apply the electric field.

Figure 1 illustrates how an electroluminescent (EL) lamp is constructed. Part A of this illustration shows the basic elements required for all EL lamps--namely a conductive base plate, phosphors (which are suspended in a high dielectric material), and a top conductive layer which is transparent to allow the light produced to be emitted.

This illustration further shows the four basic types of EL lamps. Each of these lamps has its own characteristics, and these characteristics represent certain advantages and disadvantages when considering their use from a design standpoint. Figure 1B illustrates one of the earliest lamps produced, that being the glass type. With this lamp, a rigid case is generally used, which often serves as a housing for the lamp as well as the rear conductive layer. Phosphors are then applied, and a glass faceplate, with a transparent conductor on the rear, is placed over this. The sealing is generally obtained by either

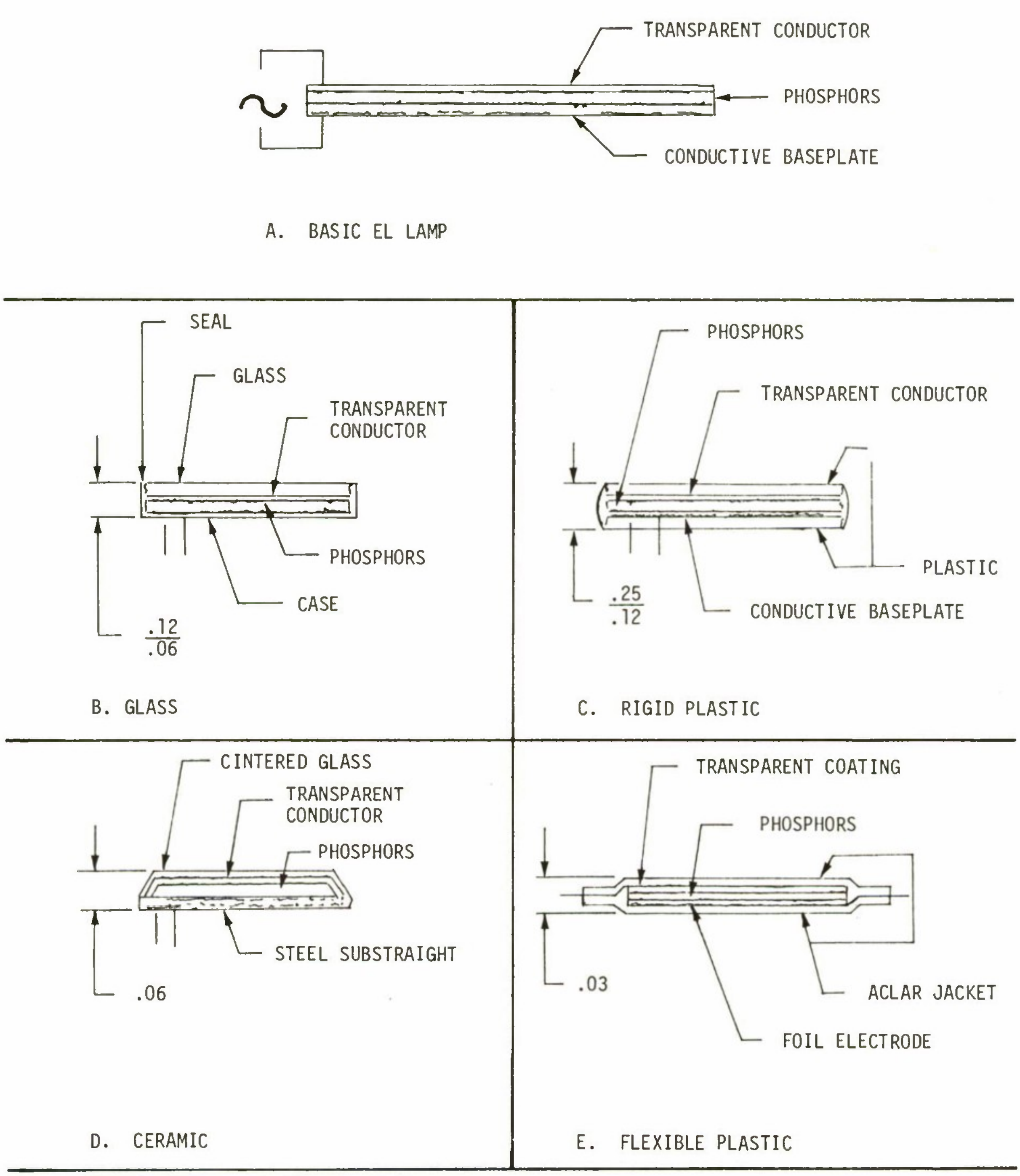

Figure 1. EL lamp construction.

soldering or cementing at the edge. Due to the nature of the materials used, this type of lamp, if properly sealed, will exhibit the best overall performance of those shown.

The rigid plastic lamp shown in Figure 1C employs either acrylic or epoxy sheets above and below the lamp sandwich, with edges normally sealed with resins or cements. To date, life has often been a problem with this type of lamp. This appears to be due to the moisture absorption rate of the plastics employed, especially the acrylics.

Figure 1D illustrates the ceramic lamp. With this type of lamp, a steel substraight is prepared to the configuration required and coated with a phosphor layer. A transparent conductive coating is applied followed by glass, which is spread in a granular form and

then sintered on at extremely high temperatures. This lamp, due to its steel substrate, is relatively heavy and often difficult to isolate electrically. It is, however, capable of exhibiting extremely long life (no doubt due to the positive manner in which it is sealed), and initially low brightness which, as will be discussed, has a significant relationship to life.

The fourth type of lamp, and that which is presently being employed to the largest extent within the aerospace industry, is the flexible plastic lamp, illustrated in Figure 1E. Essentially this lamp consists of aluminum foil which is used as the base electrode, a phosphor coating, and a transparent conductive layer. This sandwich arrangement is then laminated under heat and pressure between two thin sheets of Aclar, resulting in a final product which is approximately only .03 inch thick. Due to the extremely low moisture absorption rate of the plastics employed, and the positive sealing technique, this lamp has been found to produce exceptionally consistent life characteristics. The plastic lamp is distinguished by its flexibility, its extreme light weight (three ounces per square foot), and its preponderance of organic materials.

EL LAMP LIFE

In the above description, mention was made of the life expectancies exhibited by the various types of lamps. Further exploration of this factor is extremely necessary when considering these lamps for a design application. All EL lamps exhibit a life characteristic of the nature depicted in Figure 2. A great deal of confusion exists regarding the subject of lamp life. The question: "How much life can be expected with EL?" has often been presented, with a simple answer obviously expected. There is no simple answer. Life is truly the number of hours that a lamp will continue to produce illumination above some minimum acceptable level, and this level will, of course, vary according to the application. Further, once this level has been determined, environmental conditions, combined with a wide variety of usage conditions, greatly vary the time before it will be reached.

As indicated above, the effects of environments to which the lamp is to be exposed in operational use must be considered, especially temperature. It has been found, for instance, that elevated temperatures such as 160°F will reduce half-life to five percent or less of that which would be obtained under normal conditions. This is illustrated in Figure 2.

As discouraging as the effects of temperatures upon EL lamps may appear, there is likewise much encouragement in the manner in which lamp life can be extended by decreasing applied voltage and/or frequency. Figure 3 illustrates this point. Whereas half-life might normally be reached on a lamp operating as rated at 115 volts, 400 Hertz in less than 1000 hours, simply decreasing the applied voltage to approximately 75 volts, while maintaining the same frequency, can extend life expectancy two or three times. The brightness of the lamp is, of course, lower (approximately one-fourth but even this lower brightness will often be found more than adequate for certain design requirements, as will be discussed further. In space programs, derating of this nature has permitted life expectancies of 2000 hours or greater.

The major problem inherent in the development of a plastic EL lamp is the detrimental effect of humidity on lamp performance. It was long believed that only an inorganic material such as glass could provide this protection. The entry of moisture into the phosphor results in a shortening of the active life and causes a reduction in its light output. Moisture has an effect on the chemical composition of the phosphor, by leaching out the activators, thereby removing the active centers from the crystal lattice of the phosphor. Inclusion of moisture creates low resistance paths for current between the conductive layers, and through the phosphor and dielectric layers. This causes local heating and breakdown of the dielectric layers which, in turn, results in a short circuit between the conductive layers.

The plastic EL lamp that we make will permit lamp operation under humid conditions of 75° at 85 percent humidity for a period of one year without any effects. Under more normal conditions, this period can be expected to reach two to three years.

The outer envelope of our lamp uses a fluorocarbon plastic. It is a thermoplastic made by the Allied Chemical Company, known as Aclar. It is unaffected by most corrosive chemicals and resistant to most organic solvents, and it is flexible from -400°F to +400°F. It has excellent properties in high humidity and has low vapor transmission values.

It has been noted that the ceramic lamp displays relatively low brightness, which is .5 to 1fL, while maintaining life for extensive periods of time. An interesting experiment might be to lower the voltage and frequency on another type of EL lamp, such as the green flexible plastic (which is capable of producing 20 to 30 fL when operated at rated input) to a point where its initial brightness is two to three lamberts, and then monitoring its performance. One might very well find that the life expectancy of the lamp derated to this point would approach that of the "rule of thumb" which will be helpful, if not necessarily accurate, when

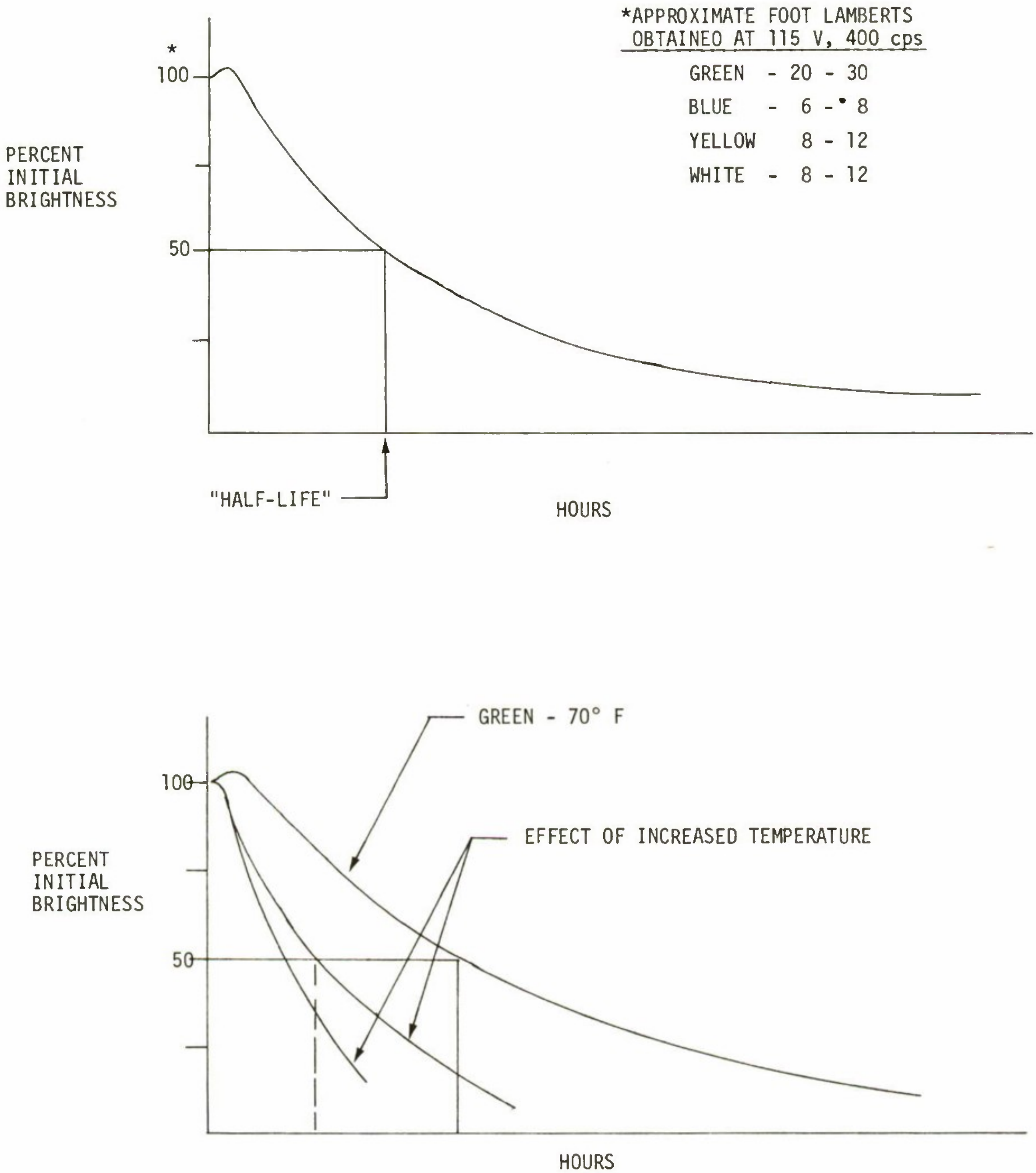

Figure 2. Typical EL life characteristics.

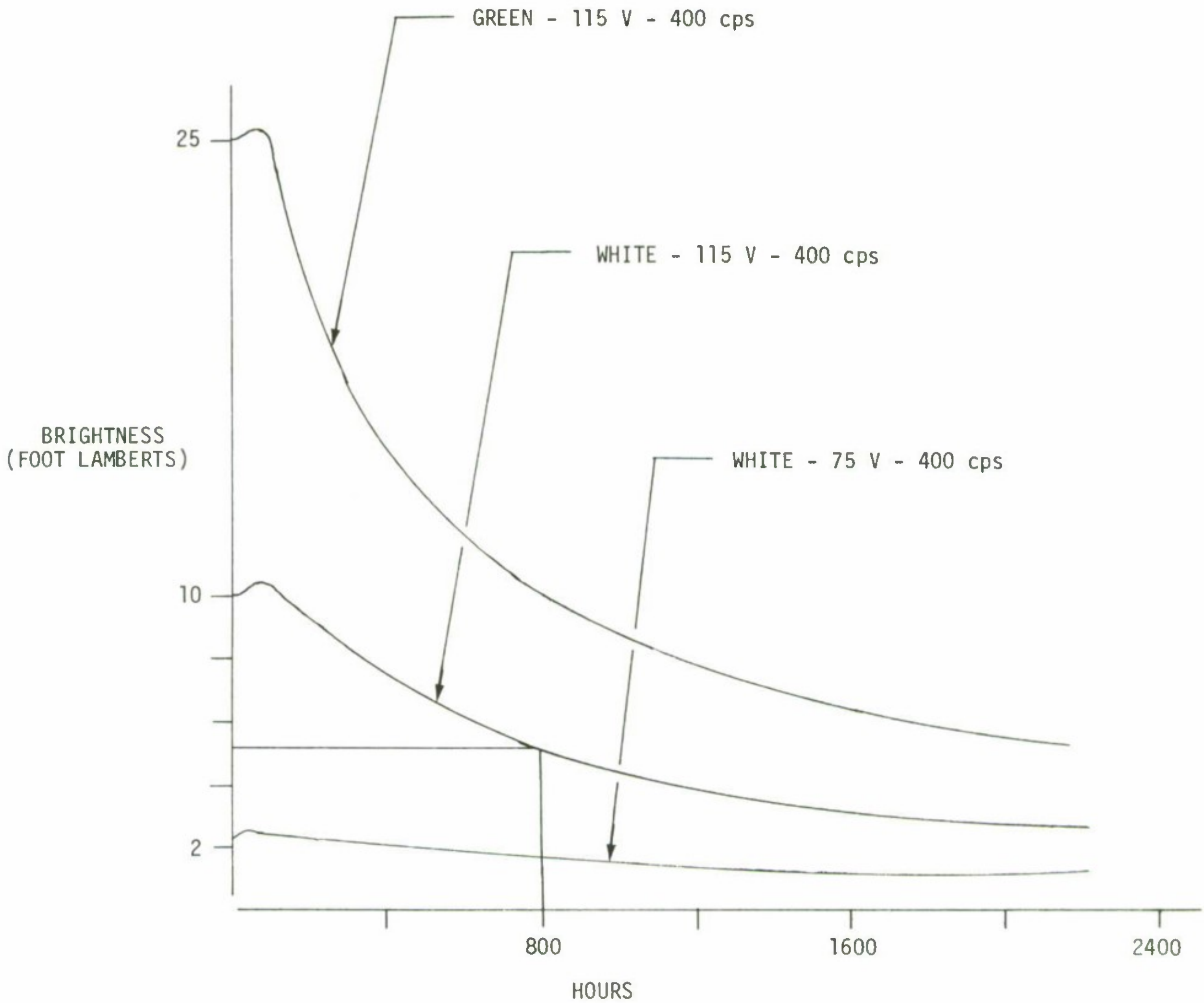

Figure 3. Effect of reduced input.

considering the application of EL. This rule is that any lamp contains a certain number of "foot-lambert-hours" which can be taken out over a brief period of time, or spread out for longer periods by accepting lower initial brightness.

LAMP COLORS

Another factor that relates to performance is color. There are three basic phosphors being used in EL lamps today, these being the green, blue, and yellow producing phosphors. These can be mixed together in certain proportions to obtain other colors, such as white. This is illustrated on the CIE diagram in Figure 4. This figure illustrates how, by mixing blue and yellow phosphors within a lamp, the two colors will add together, as is also illustrated in Figure 4, to produce a white. This color will fall on a line drawn between the points representing the color coordinates of each mixing proportion. This is known as a "two color mix" and is somewhat easier controlled than a "three color mix," where green phosphors are also introduced to vary the shade of white toward green.

With the color mixing techniques described above, it will be found that a change in the resulting color will take place over a period of time, since not all phosphors have the same life expectancy. This problem is not encountered in another technique, in which a lamp of one basic color is used in conjunction with fluorescent paints which are applied as an overlay over the lamp. This is illustrated in Figure 5. White can also be produced in this manner, either by using a pink fluorescent overlay on a green lamp or a blue fluorescent overlay on a yellow lamp. The overlay will fluoresce when subjected to light energy, the energy in this case being that of the EL lamp, producing a color in accordance with its basic characteristics. If the overlay is applied as a very thin coat, it will also leak

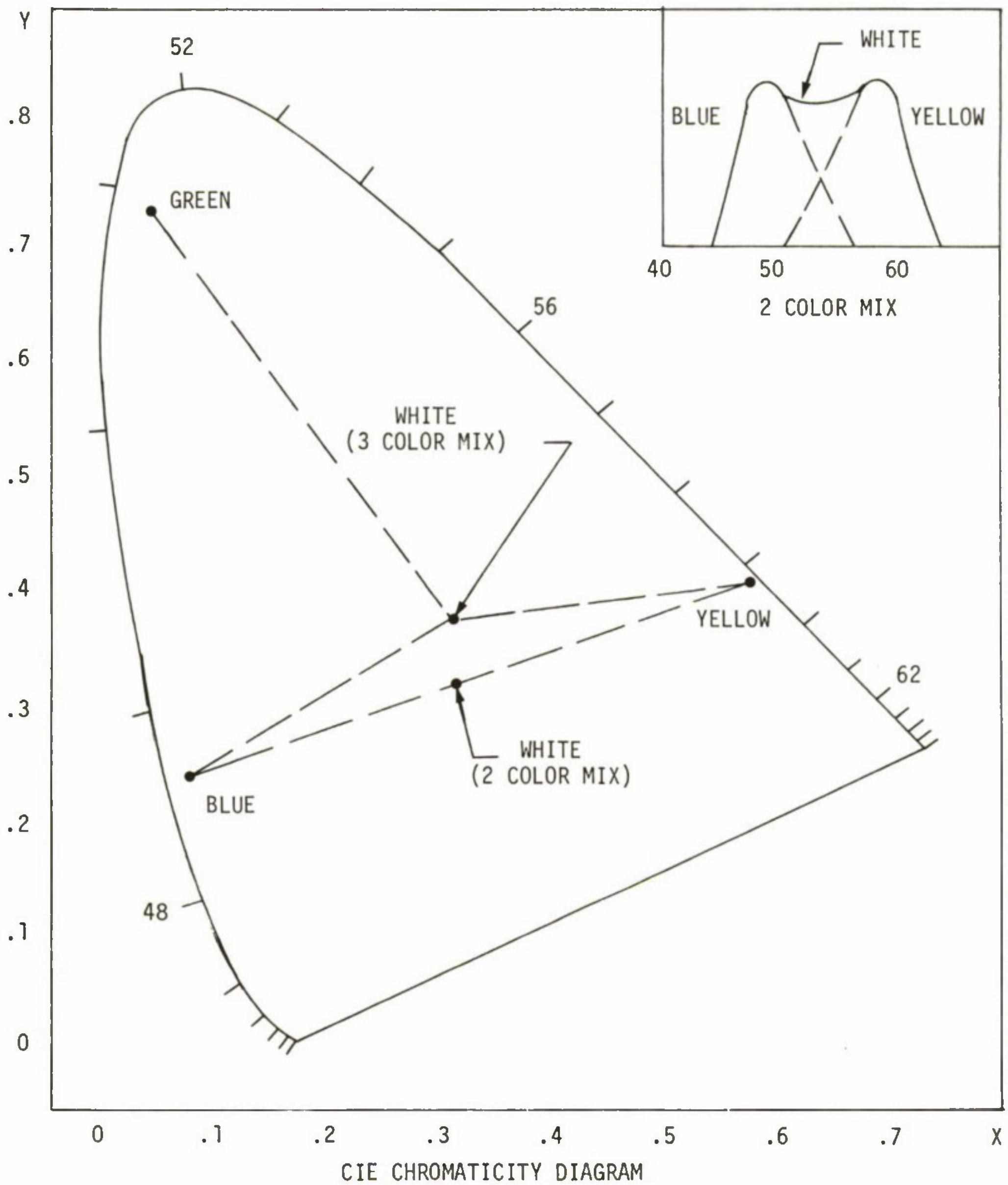

Figure 4. Color mixing within EL lamps.

light from the lamp itself and the resulting color will be the mixture of the two. The fluorescent overlay is far less effective than the lamp itself, and the heavier it is applied the more the lamp is "smothered." Therefore, as the color approaches that of the overlay, the resulting brightness becomes less. This explains one of the reasons why industry has experienced a great deal of difficulty in attempting to obtain red from electroluminescence. As can be seen in this illustration, a large amount of red fluorescent material is required in order to sufficiently shift the resulting color into the red region. This is normally done by applying this material to a green lamp because the green lamp is more efficient than other colors to begin with. However, the resulting brightness from this system will be ten percent or less of that obtained with the green lamp initially. Consequently, when operating at full rated input, red lamp brightness values of only two or three foot lamberts can be obtained.

White EL lamps, produced either by the two phosphor mixes or overlay system, will generally produce 8 to 12 foot lamberts when operated at 115 volts--400 Hertz. In this fact alone lies one of the biggest reasons why white electroluminescence is currently more promising than red for design application. The white lamp can be derated considerably,

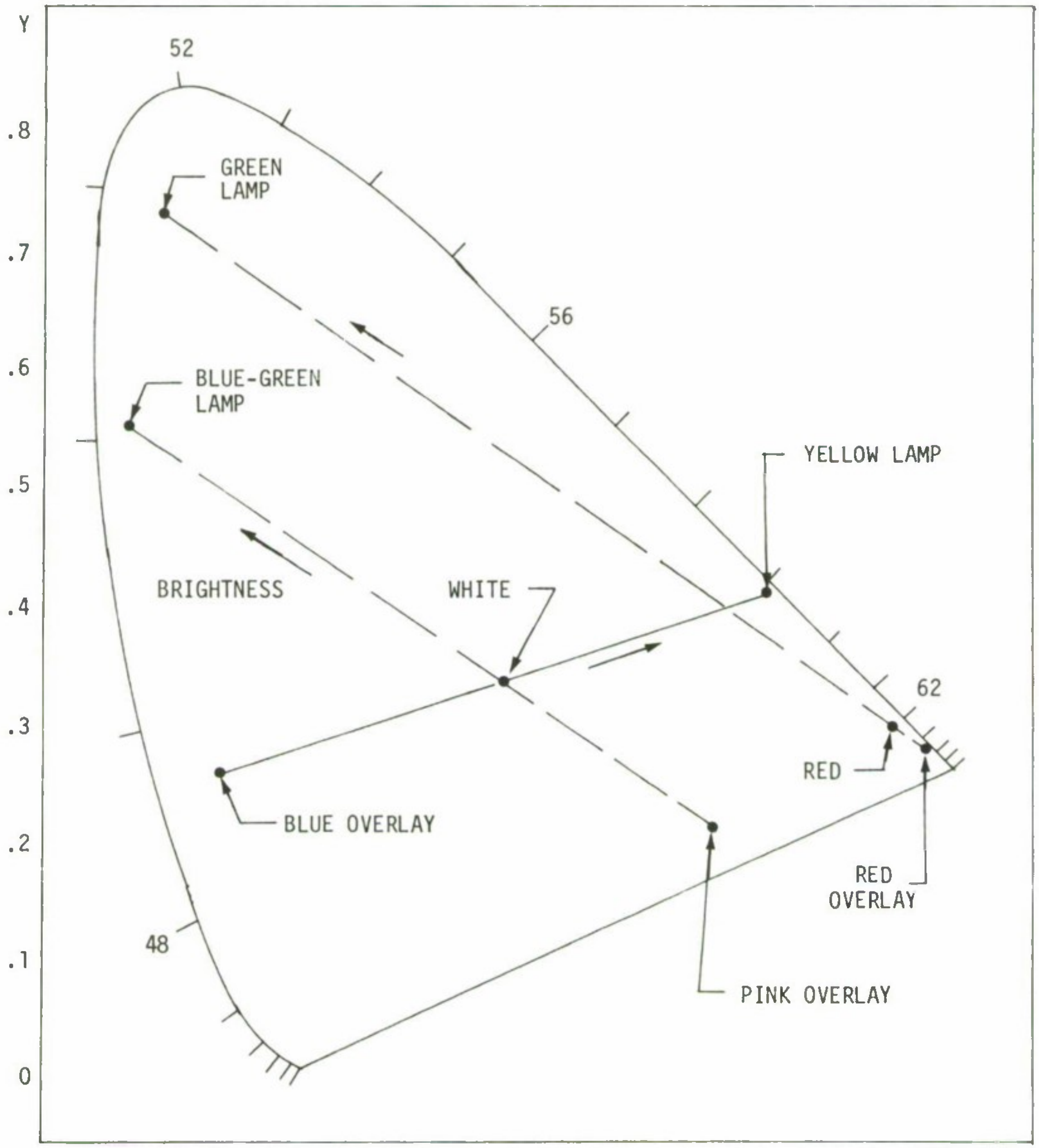

Figure 5. Color mixing with overlays.

with life therefore extended, while still producing the same brightness as can be obtained with the best red systems available.

When considering EL for application within a crew station, the following points must therefore be weighed: 1. What are the color and brightness requirements that will be necessary to achieve the proper illumination for the vehicle in question? 2. What minimum brightness will be acceptable before panel replacement will become necessary? Will ground time be part of this life, or will operation of the lighting be monitored throughout the life of the vehicle so that such time can be restricted or eliminated? 3. Are there lamps available that will produce this color and brightness over the life span established? If the answer to the third question is positive, the rewards of an electroluminescent system can be made available.

DESIGN CRITERIA

The following considerations must be recognized when an EL lamp is designed into a system.

Lamp tolerances. Standard tolerances on all dimensions ±.03 for lamps up to a size of 30 square inches, ±.06 on lamps of over 30 square inches or more than a six to one

length-to-width ratio. Any lamp tolerance below these standard tolerances will necessitate an increase in price of the lamp. In no case should the tolerances be less than ±.015, even on small lamps.

Unlighted seal area. The distance on small lamps is 1/8-inch average size of eight to ten square inches and from 1/8-inch to 1/4-inch on larger lamps. Use 1/4-inch on lamp sizes of two inches by six inches and larger. We also desire a 1/4-inch seal on the lamps that have a length-to-width ratio of more than six to one. All holes and cutouts should have a 1/8-inch unlighted area on each side.

Unlighted seal area contact area.
Type "A" mesh leads 1/8-inch minimum required.
Type "B" mesh leads with eyelets 3/8-inch minimum.
Type "C" tab connection 3/8-inch minimum.
Type "D" connection terminal with wire leads 3/8-inch minimum.

DESIGN DATA REQUIREMENTS

- Voltage and frequency.
- Lighted area and overall area.
- Color and intensity requirements.
- Type of electrical connection.
- Environmental specification.

SUMMARY

EL lamp characteristics and EL panel characteristics are summarized in Tables 1 and 2, respectively.

TABLE 1

EL LAMP CHARACTERISTICS

COLOR	COLOR COORDINATES X ±.030	Y ±.030	VOLTS	HERTZ	BRIGHTNESS-FOOT LAMBERTS
GREEN	.230	.525	115	60	5.0 ±2.0
GREEN	.220	.510	115	400	18.0 ±3.0
STANDARD WHITE	.355	.375	115	60	2.0 ±1.0
STANDARD WHITE	.290	.310	115	400	6.0 ±2.0
RED (CONVERTED)	.690	.300	115	60	.5 ± .2
RED (CONVERTED)	.690	.300	115	400	2.0 ±1.0
YELLOW	.535	.465	115	60	2.0 ±1.0
YELLOW	.530	.460	115	400	6.0 ±2.0

TABLE 2

EL PANEL CHARACTERISTICS

COLOR	COLOR COORDINATES X ±.030	Y ±.030	BRIGHTNESS-FOOT LAMBERTS AT 115 VOLTS, 400 HERTZ
GREEN	.230	.530	6.0 ±1.5
STANDARD WHITE	.320	.340	2.0 ±1.0
AVIATION RED	.690 ±.010	.300 ±.010	.50 ±.20

VSTOL TERMINAL GUIDANCE HEAD-UP DISPLAYS: A REAL WORLD EVALUATION

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NAVAL AIR TEST CENTER

Abstract: *The inability of present-day instrument displays to provide an all-weather approach in VSTOL aircraft and the failure of simulator developed displays to provide usable display formats and dynamics without expensive changes after production has led the U. S. Navy, through the NAVAIRSYSCOM, to develop a real world evaluation of head-up displays for VSTOL. The test bed will be a CL-84 twin turbo-prop tilt wing airplane which is capable of flying safely throughout the VSTOL transition range, with accommodations for a subject pilot, a flight safety pilot, and sufficient room/power for the programmable display avionics and data recording systems. Prime emphasis will be on a data related pilot performance evaluation of the head-up display and its dynamics for terminal guidance.*

BACKGROUND

The U. S. Navy (NAVAIRSYSCOM) is developing display systems for a wide range of aircraft and mission requirements. These systems have, for the most part, been developed independently, and the interactions between a variable head-up display (HUD) and the pilot have not been evaluated in a development flight test program.

The evaluation of various levels of information display via a HUD should be performed in an aircraft type which covers a wide spectrum of flight characteristics. An aircraft such as a tilt-wing VTOL can be utilized as the test vehicle for these systems. The aircraft should be representative of a class of aircraft which is anticipated for U. S. Navy use during the next decade. Additionally, development of existing head-up display systems has invariably been paced with changes to software that improves symbol shape or dynamics. The requirement for these improvements was not realized until the display had been flown in the real world. This costly problem is best labeled as a transfer function out of the simulator.

Further, when gathering subjective data, there is a tendency on the part of the pilot community to have strongly voiced opinions as to what is required in the symbol size, shape, and format. The strength of these voices tends to vary with rank and not experience. The U. S. Navy would like to convert this into pilot performance versus preference.

WHY A HEAD-UP DISPLAY IN VSTOL?

The helicopter community has long since taught us that in the terminal maneuver, skill is achieved through the use of the streaming effects of real world cues more than from instrument information. It appeared logical to include much of the outside world in the transition from IFR flight and to make the instrument flight relate to the real world. Therefore, taken that a costly transfer function from the simulator exists and that a head-up display is needed in VSTOL aircraft, the need for a test and evaluation (T&E) vehicle that would provide a programmable display, provide reasonably stable and safe flight throughout the transition range, have a dual control capability, the space/electrical power for the associated avionics and the data recording system was apparent. We believe that the vehicle to accomplish this task is at hand in the CL-84 twin turbo-prop tilt-wing VSTOL vehicle.

OBJECTIVE

The objective of this work is to conduct a flight evaluation of the head-up display symbol size, shape, format, and dynamic requirements for VSTOL terminal guidance through operator performance measurement.

METHOD

The United States, U. S. Navy Agency; United Kingdom, RAE Agency; and Canada, DND Agency have joined resources and expertise to provide the requisite T&E capability to perform this evaluation. The U. K., because of its HUD interests in the AV-8A Harrier and its considerable VSTOL display experience, has provided a programmable HUD. The Canadian Government has provided the CL-84 airplane as the test vehicle. The U. S. is providing the instrumentation and data-reduction capability plus the use of the SPN-42 data-link facility at NAS Patuxent River, Maryland. The total effort is covered by a tripartite Memorandum

of Understanding.

Each country will provide two pilots with VSTOL and HUD experience. These project pilots will utilize the airplane for a one-year period that will schedule 100 data flight hours.

The flight test program will be broken into four distinct phases. Phase zero is presently in progress and consists of the installation of required avionics and instrumentation plus pilot training on systems and airframe. The first flight phase will have the U. K. providing the design of experiment and test direction. This test phase will concentrate on an RAE-developed display format that is geared to improving the Harrier night-flying ability.

The second phase, directed by the U. S., will be evaluating the NATC-developed display format. Additionally, different approach angles will be evaluated with a range of from 3 to 15 degrees. The basic difference between the two display formats is that the U. S. scheme is a 1:1 scale with a contact analog runway or landing pad symbol. The RAE format is more of a compressed situational display.

The third phase will be an evaluation of the best result combination of the previous two phase efforts. Since all the work up to phase three will only bring the vehicle to a hover, an instrument vertical descent may be examined in phase three. Commencement of phase one is scheduled for mid October 1972. Data collection will be in the form of on-board magnetic tape. The digital output of the display, aircraft motion, pilot activity, and aircraft position relative to desired flight path (from the SPN-42 data link) will be collected during those portions of the flight that are considered to be significant. The flight tape will be processed and strip charts made as required. Data reduction will be accomplished on a Varian 620i computer programmed for statistical analysis of the pilot activity. Simply stated, a specific display error or command will be referenced to the appropriate pilot control. This in turn is compared to actual flight path performance. Statistical summaries will be made of the relevant parameters and analysis of their value and power will be made.

The decision for the display format or control laws from one flight to the next will be based upon this information and will be the responsibility of the test director. Subjective evaluation from the pilots will of course be taken and compared with detail performance.

It is our firm hope that by next year the tripartite management committee of this program can present the results of a real-world evaluation based upon performance, not preference, and can show that this method of determining display software requirements is valid and perhaps cost effective.

COCKPIT GEOMETRY WITH NONADJUSTABLE SEATS

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Abstract: *Past and present crew station geometry has required an adjustable crew seat to allow the full range of pilots to position themselves on a horizontal vision line to insure optimum external vision.*

This paper presents a new concept in cockpit geometry wherein seat adjustment is no longer required. This is achieved by providing the required downward vision angle from the design eye position of the small pilot when seated on a fixed (nonadjustable) seat and providing the required upward vision angles from the design eye position of the large pilot seated in the same seat.

The benefits of this concept are not limited to external vision, but also result in effective control location and actuation, increased internal vision, accessibility of controls located on side consoles and instrument panels, reduced rudder pedal adjustments, reduced seat structure weight, increased survival kit volume, increased throttle, and rudder pedal/brake actuation.

INTRODUCTION

After the "bicycle makers" diverted their attention to making like birds, early aeroplanes were built with an enclosure for the aviator to protect him from the propeller windblast, slipstream, castor oil, and carbon particles from the propeller and engine mounted on the front end of the flying machine. This was a real "biggy" as far as the pilots were concerned. However, when the flying craze caught on, and student trainees of all shapes and sizes started showing up at the local flying field schools, a problem soon materialized when they climbed over the coaming and sat down in the wicker chair. Some could not see out, others were sitting above the windshield. It must have been then that someone suggested," Why not make the chair adjustable?" The utterance of these simple words has had a marked effect on cockpit design through the years, and this is why I am up here today. I would like to touch briefly on a new solution to an old problem.

PRESENT COCKPIT GEOMETRY

Our present cockpit geometry requirements (Figure 1) specify that pilot ejection seats will have a five-inch vertical adjustment to allow the 5th and 95th percentile pilots to reach a design eye position for optimum external vision. This adjustment is measured from the neutral seat reference point (two and one-half inches upward, two and one-half inches downward). However, the current method of meeting this requirement is to allow the seat to move up and down the ejection rails which are canted depending on the

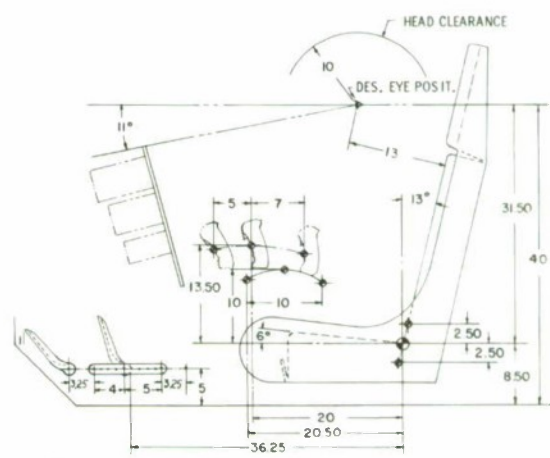

Figure 1. Present cockpit geometry.

ejection angle. This angle introduces a design inconsistency in that when a 5th percentile pilot adjusts the seat upward to reach the design eye position, the seat moves up and *aft* and he moves away from the basic flight controls, instrument panel, throttles, side consoles, and rudder pedals. Conversely, when a 95th percentile pilot adjusts the seat downward, the seat moves down and *forward* and he moves closer to the flight controls, instrument panel, throttles, side consoles and rudder pedals. To alleviate the resulting rudder pedal/leg reach problem of the 5th and 95th percentile pilots, a considerable range of rudder pedal adjustment (nine inches) must be provided when the seat is adjusted to the full up and full down positions.

The control stick grip must be positioned

abnormally high in the cockpit to clear the forward edge and top surfaces of the survival kit when the seat is in the full up adjustment and the stick grip pulled full aft. This creates a comfort problem for the 95th percentile pilot when the seat is full down in that the stick grip is too high for optimum use.

GEOMETRY STUDY

Figure 2 portrays a study currently being conducted utilizing a nonadjustable seat in a fighter-type cockpit. The basic purpose of this study is to provide the 5th percentile pilot with the required minimum external downward vision from his eye position when seated in the fixed reference point seat. This is to say that the 5th percentile pilot in this geometry would achieve the same external vision as he would in the current geometry with the seat in the full up adjustment. All external downward vision requirements would be established from this eye position in the cockpit.

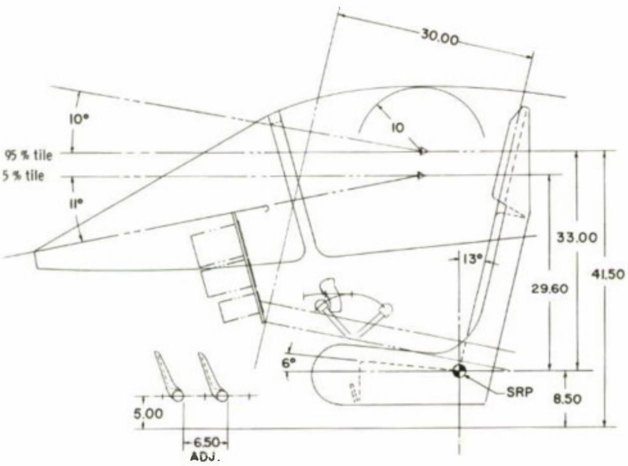

Figure 2. Nonadjustable seat cockpit geometry.

All external upward vision and head clearance requirements would be based on the eye position of a 95th percentile pilot seated in the same fixed reference seat. With this rationale, any pilot larger than the 5th percentile would have greater external downward vision than he could achieve when properly seated in the current cockpit geometry, and there would be no decrease in upward vision. Since the 10-inch head clearance is based on the design eye position of the 95th percentile pilot, an increase of one and one-half inch in canopy height compared to present geometry requirements will be required. This will increase the weight and aerodynamic drag of the canopy. It is interesting to note however that the vertical height of this canopy compared to the F-15 canopy is approximately four inches less. Nevertheless, structural and aerodynamic drag considerations must be given by the airframe manufacturer because of the one and one-half inch height increase. Since the fixed seat reference point is eight and one-half inches above the heel rest line, additional space becomes available under the reference point which could be used for critical survival equipment.

A problem with this concept arises with respect to the varying eye position of the 5th percentile through 95th percentile pilots seated in the nonadjustable seat. The variation in eye height is three and four-tenths inches which has a direct bearing on the alignment of the pilot's eye and gunsight/head-up display in the cockpit. Helmet mounted gunsights currently being considered may resolve this problem. Possibly an adjustable gunsight or HUD combining glass could be used to accommodate the range of eye positions.

With a nonadjustable seat concept, the cockpit geometry can be designed to the actual physical anthropometric differences between the 5th and 95th percentile pilots and not compromised with a five-inch vertical seat excursion. For example, with the 5th and 95th percentile pilot seated at the same seat reference point, the rudder pedal adjustment is only six and one-half inches as opposed to the current nine-inch adjustment requirement (see Figures 3 and 4). In addition, the brake pedal "OFF" angle and the pilot's foot/tibia angle remain relatively constant since there is no variation in the seat reference point height. Ejection clearance, both longitudinal and lateral, remains unchanged from current requirements.

Lateral downward vision over the canopy sill is based on the 5th percentile pilot eye position with his head rotated 90° to the side (see Figure 5). Figures 6 and 7 show the 5th and 95th percentile pilots with respect to lateral clearance and throttle accessibility. Because of lowering the design

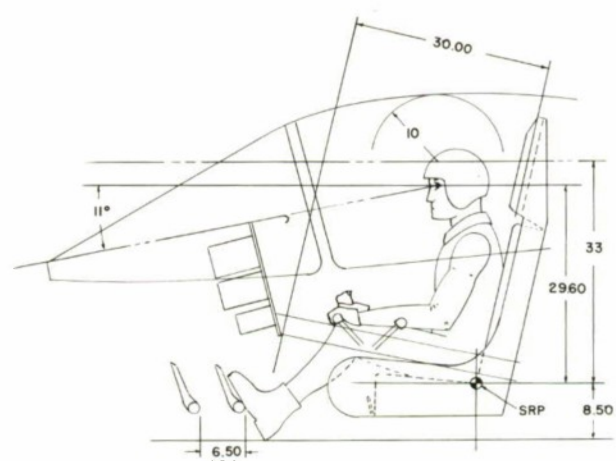

Figure 3. Fighter cockpit, 5th percentile.

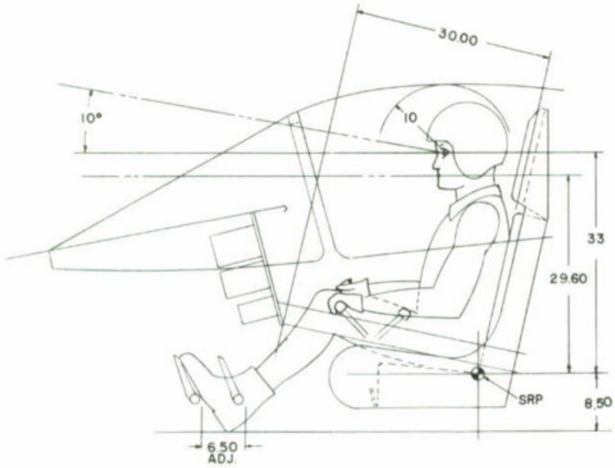

Figure 4. Fighter cockpit, 95th percentile.

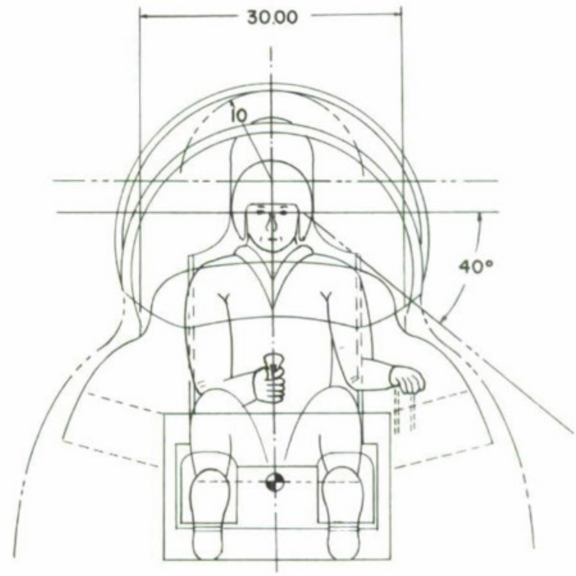

Figure 6. Fighter cockpit lateral clearance, 5th percentile.

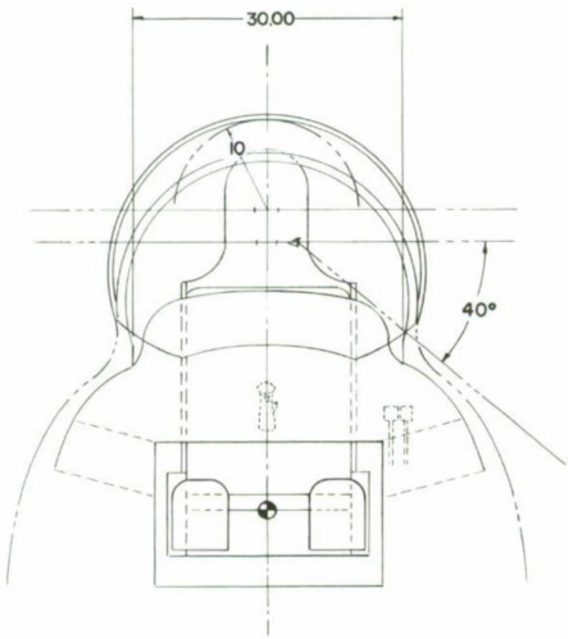

Figure 5. Nonadjustable seat cockpit geometry.

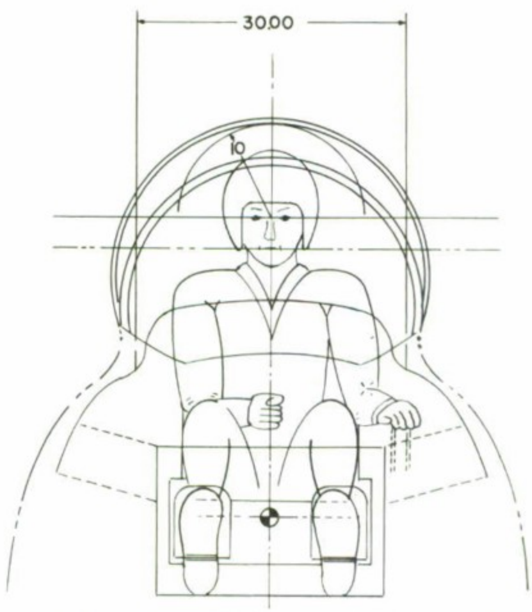

Figure 7. Fighter cockpit lateral clearance, 95th percentile.

eye position of the current cockpit geometry to the level of the 5th percentile pilot, a loss of one and three-fourths inch of vertical instrument panel height is effected. An instrument panel layout is shown in Figure 8, and sufficient panel space is still available for advanced flight and engine instrumentation, armament, and miscellaneous controls and incicators. Figure 9 is a proposed cockpit geometry layout with tentative location and ranges of motion of the basic flight controls and clearances. Of major importance are: the reduction of rudder pedal adjustment to six and one-half inches, and lowering of the control stick grip to 12 inches, and the throttle to ten and one-half inches above the seat reference point. The seat headrest can extend upward to the canopy since the seat does not adjust and as a result can insure that the 95th percentile pilot's helmet will not strike the canopy first in a through-the-canopy ejection.

Wheel controlled cockpit geometry was investigated and similar advantages were found with respect to external vision, rudder pedal adjustment, and the lowering of the

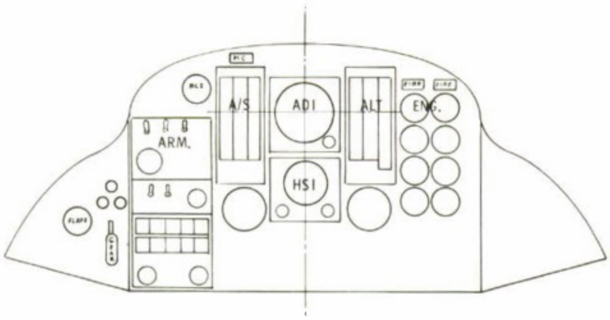

Figure 8. Instrument panel layout.

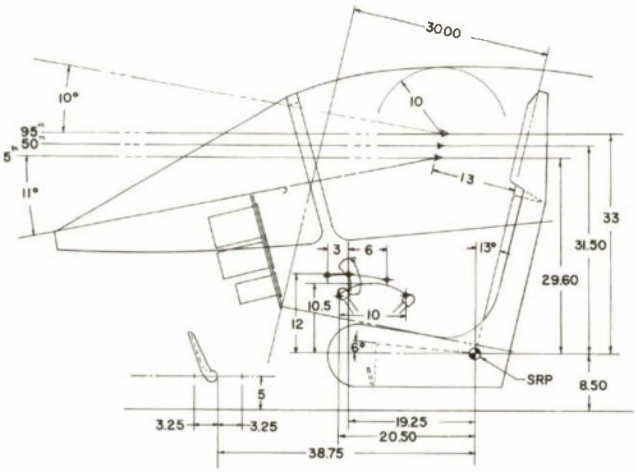

Figure 9. Proposed cockpit geometry.

control wheel (see Figures 10 and 11). Control wheel height in the current geometry has been extremely critical with respect to thigh clearance when the seat is in the full up adjustment. With a nonadjustable seat, the wheel can be lowered two inches and as a result increased instrument panel vision is provided. Figures 12 and 13 show the 5th and 95th percentile pilots in their normal flight position. Figures 14, 15, and 16 show the lateral clearance, pilot accessibility to consoles and throttle, and lateral external vision requirements.

MAJOR ADVANTAGES

In summary, the non-adjustable seat concept has the following major advantages over an adjustable seat.

- The 5th and 95th percentile pilots are not malaccommodated with a seat that moves up and aft along a diagonal.
- No seat actuator (electrical, mechanical, wiring, switches, power requirements) is required.
- All pilots have the required external vision.

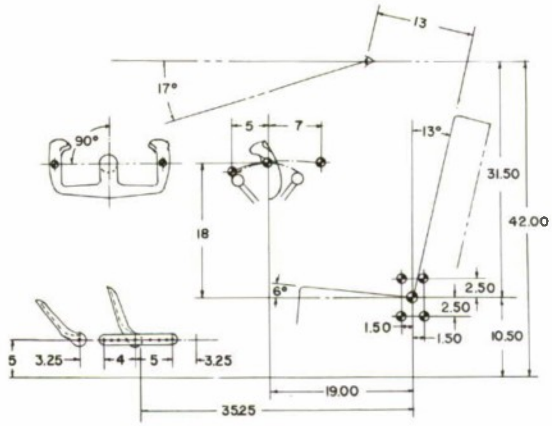

Figure 10. Present wheel controlled cockpit.

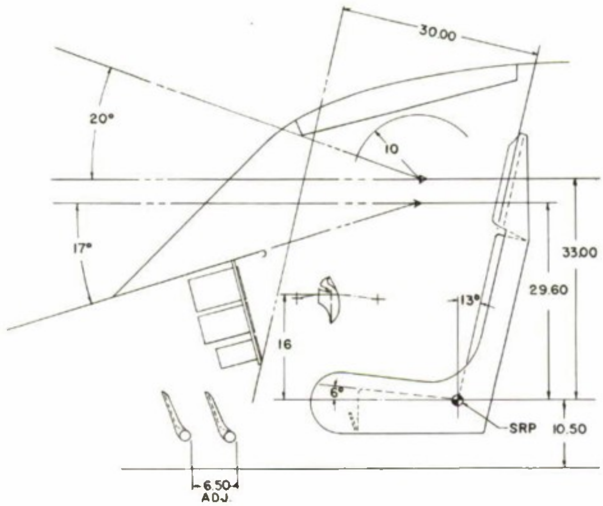

Figure 11. Nonadjustable seat wheel controlled cockpit.

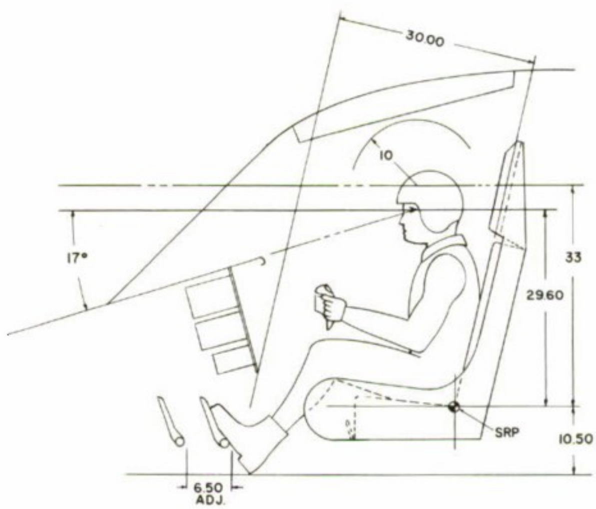

Figure 12. Wheel controlled 5th percentile.

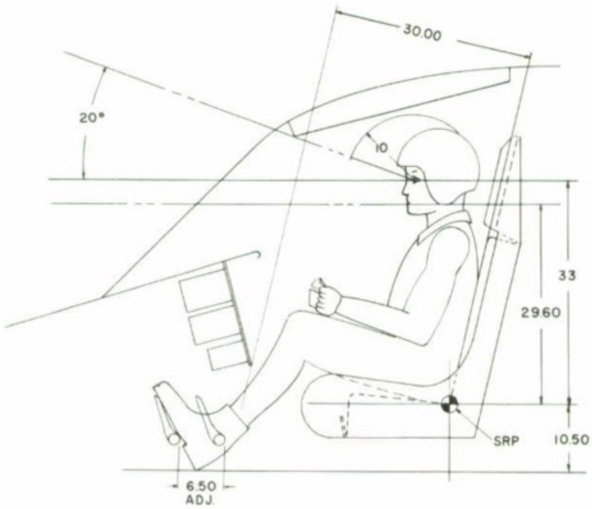

Figure 13. Wheel controlled, 95th percentile.

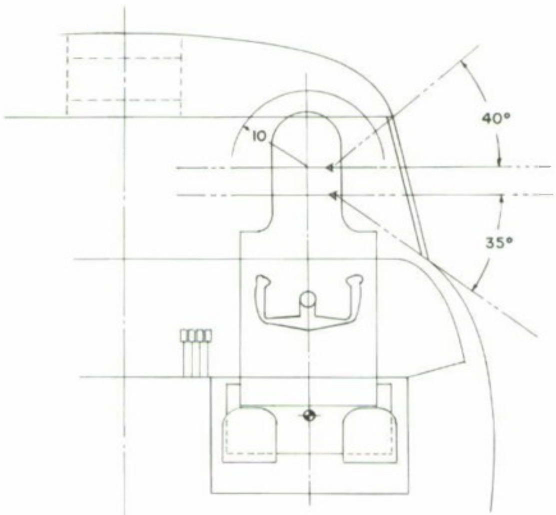

Figure 14. Wheel controlled lateral clearance.

- Additional survival kit space is available under the seat cushion.
- Adequate head clearance is provided for all pilots.
- Throttle and side console accessibility is greatly improved for all pilots.

DISADVANTAGES

- A one and one-half inch increase in canopy height is required.
- A one and three-fourths inch reauction in vertical instrument panel height is necessary.
- HUD/gunsight/pilot eye alignment may be a problem.

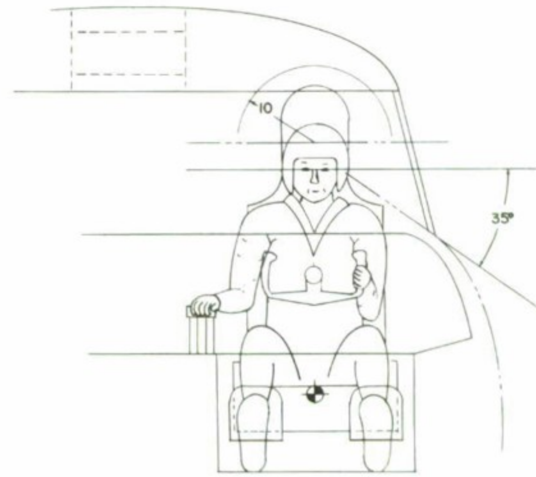

Figure 15. Wheel controlled lateral clearance, 5th percentile.

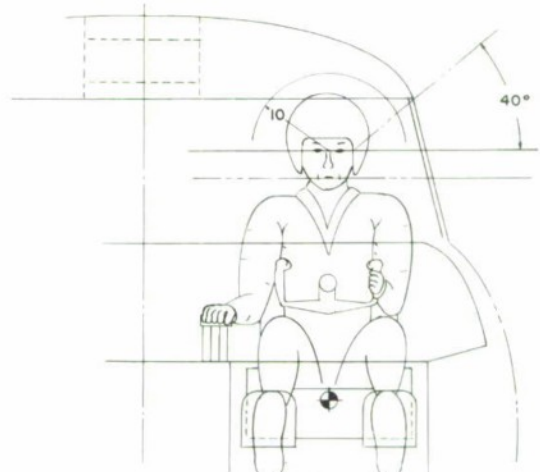

Figure 16. Wheel controlled lateral clearance, 95th percentile.

- Not adaptable into existing aircraft without major modifications to the airframe.
- Pilot reorientation to a nonadjustable seat would be required.

A full scale mockup is currently being fabricated at ASD to investigate all aspects of cockpit design using this concept. When it is completed, a comprehensive evaluation will be conducted using rated pilot subjects, personnel subsystem analysts, and crew station design engineers. Upon completion of this evaluation, a technical report will be prepared in detail covering the mockup design, construction, evaluation, advantages, disadvantages, problem areas, pilot comments, conclusions, and recommendations.

OPERATOR WORKLOAD: WHAT IS IT AND HOW SHOULD IT BE MEASURED?

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Abstract: *The term "operator workload" generally refers to an integrative concept for evaluating the effects on the human operator associated with the multiple stresses occurring within man-machine operating environments. Viewing the human operator's role in man-machine systems as that of an information transfer and transformation component, a case is made for considering workload as consisting of three functionally relatable aspects: input load, operator effort, and work result. Workload measuring techniques having their basis in time-and-motion analyses, information processing experiments, and direct physiological measurement of the operator state are briefly discussed. The initial conceptualizations of a long-range research program are indicated, where the objective is the systematic investigation of operator effort exerted relative to specifiable input loads and performance criteria.*

INTRODUCTION AND BACKGROUND

When I started my job in Germany several months ago, I was given the task of developing and applying workload measurement techniques and methodology. Since I was somewhat familiar with the cockpit crew workloading model developed by Dickey (1969) and its foundation in the work of Art Siegel and his associates (Siegel & Wolf, 1961, 1969), I thought, "O.K., that looks like an interesting problem which could probably use some refinement." However, as I surveyed some additional literature which purportedly dealt with the subject of "operator workload," I was overwhelmed by the diversity, and often vagueness, in the way the term is defined and used. I came to the conclusion that the four categories shown in Table 1 encompass most origins of the concept in vogue today. There are, of course, some overlaps among the representative examples cited across categories, but I believe that the basis and direction of research is determined to a large extent by the corresponding individual categories.

The different definitions of workload used within each of the categories can be interpreted in the following manner:

Time-and-motion studies: percent of time required to complete a given set of tasks within a fixed available time period.

Information processing: assuming that the operator possesses a fixed, limited channel capacity, workload is the ability to accomplish additional (expected or unexpected) tasks.

Activation theory: Task demands influence the activation level (physiological state) of the human and thus operator energy expenditures.

Design implicit: usually no definition is given, but the gist is that any design changes which can be associated with operator performance improvement must also have reduced his workload.

TABLE 1

ORIGIN OF OPERATOR WORKLOAD CONCEPTS

WORKLOAD CONCEPT ORIGIN	REPRESENTATIVE EXAMPLES
TIME-AND-MOTION STUDIES	SIEGEL & WOLF (1961, 1968), LINDQUIST (1972), DICKEY (1969), HOPKIN (1972), MURPHY & GURMAN (1972)
INFORMATION PROCESSING	LEVISON (1969), LEVISON *ET. AL.* (1971), KELLEY & WARGO (1967), TRIGGS (1969), VAN GIGCH (1970), CLEMENT *ET. AL.* (1972)
ACTIVATION THEORY	CUMMING & CORKINDALE (1967), HOWITT (1969), LITTELL (1969), KALSBEEK (1968, 1971), RADL (1969), HAIDER (1972)
DESIGN IMPLICIT	ALL THOSE STUDIES WHICH CLAIM THAT BY "SIMPLIFYING" THE OPERATOR TASKS WORKLOAD IS AUTOMATICALLY REDUCED.

Although these definitions differ somewhat from each other, it may be more a difference in level of detail included rather than a difference in kind. All concepts are essentially based on the premise that the primary role of the human operator in man-machine systems is that of an information-receiving,

processing, and/or transmitting element, and that workload measurement deals with the demands placed on the human operator in the course of transfer and transformation of inputs into outputs. Thus, as Benson (1969) has pointed out, workload has been introduced as an integrative concept for studying the effects of multiple stresses within the man-machine operating environment on the human operator.

An example of the procedures used in a time-and-motion type workload evaluation method is shown in Figure 1 which was adopted from Zipoy and his associates (1970). Generally, mission profiles, scenarios and function allocations used in developing crew stations are also used to identify and select those critical mission phases of highest inherent complexity and number of system tasks. A task analysis is conducted to list and sequence the operator tasks required to complete a given mission phase. Task completion times are assigned based on the best available experimental data and summarized on timeline plots to provide an overview of phase activities. Determination of the appropriate operator channel for each task is based on an examination of the task performance characteristics and the crew station control/display layout. The time-per-channel budgeted to a particular task is determined by comparing task completion times with mission-phase time requirements and then distributing the available time over the various tasks. The computer run produces operator effort summary statistics and graphs for the various operator channels used during the mission phase and for individual time segments of the phase. Operator workload here was defined as the total time a given channel and/or combination of channels was used during mission segments of interest.

The time-and-motion type operator workload assessment techniques provide an adequate tool for making general, broad predictions regarding the operator's ability to handle a given set of tasks. They are heavily dependent, however, on the adequacy of task sequencing in relation to actual operator behavior and on the accuracy of the task completion times used. In other words, they are highly deterministic and tell us whether the human operator can or cannot handle the tasks assigned to him if he will behave in the manner prescribed for him. Used quite early during the crew system design process, they can point out general design deficiencies and data requirements for achieving refined operator performance assessment in subsequent stages of the system development cycle.

Techniques which use evaluation of excess channel capacity as a measure of operator workload were mainly developed in part-task simulation settings (Knowles, 1963). Although they provide valuable data on the strategies and capabilities an operator uses in handling specific individual loading conditions, they may actually distort the picture when we try to apply them to the complex interactions of task loadings experienced in

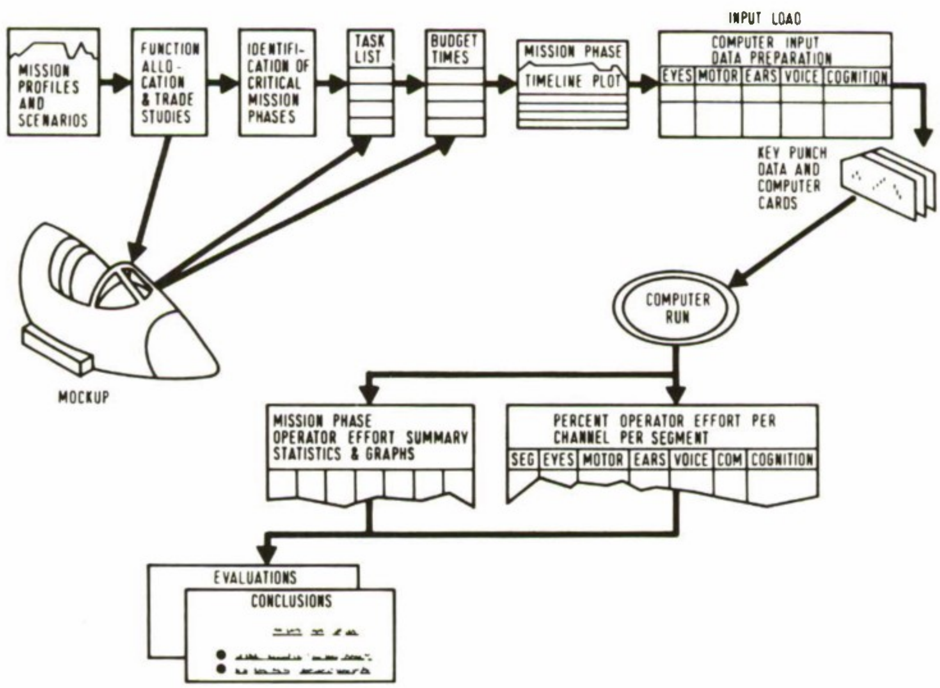

Figure 1. Example of time-and-motion type operator workload evaluation method.

higher-order man-machine systems (Chapanis, 1967). The secondary or adaptive tasks used in experiments for determination of excess channel capacity often appear far too artificial relative to those found in operational man-machine systems. The argument that secondary task performance is not of direct interest may hold for laboratory studies of specific operator capabilities, but it ignores the synergistic nature of "real-world" tasks; and thus makes available data suspect with regard to applicability in the crew system design process.

Finally, we have physiological measurement of the operator. With these techniques, which by the way are especially popular in Europe, changes in such things as heart rate, sinus arrythmia, EEG, cortical evoked potentials, integrated EMG, respiration rate among others are correlated with various task loads, ranging from those found in aircraft landings (Howitt, 1969; Cumming & Corkindale, 1967), through ATC situations (Kirchner & Laurig, 1971) to the playing of a symphony by various members of an orchestra (Haider, 1972). The results obtained so far are promising but fraught with problems in measurement techniques, data reduction, and interpretation. One of the biggest problems is the huge inter- and intra-individual variability in physiological parameters. Physiological indices have, of course, already been sensed and processed to predict the potential breakdown of the operator subsystem and to prevent the breakdown by changing the input load as exemplified by the procedures used with astronauts, but these cases involve primarily motor efforts rather than cognitive efforts exerted by the operator. It would be nice if we could stick a general purpose metering device on human operators to measure how much effort they are exerting for learning, decision-making, or daydreaming, however, we will probably have to wait quite a while before such a tool will be available to assist us in the crew system design process (Sanders, 1971).

WORKLOAD ASSESSMENT REQUIREMENTS

So, where do we stand, and where do we need to go? In general, the approach to workload research has been either too molecular (e.g., physiological parameters in isolation) or too molar (e.g., digital simulation models) to provide the broad spectrum of data required during the various phases of crew system design. A number of potentially useful techniques are available to partially provide meaningful, quantitative answers on the myriad of parameters influencing operator effort in man-machine system operations. These techniques need to be systematically evaluated and integrated in the specific context of crew system design requirements. We must begin to look at and handle the overall integrated complexity of man-machine-environment systems. That is, we have to provide a taxonomic structure for all parameters which can influence the operator in order to be able to provide meaningful and comprehensive answers to questions arising during the crew systems design process on the matter of workload. Chapanis discusses the requirement for data applicability in crew systems design and operation quite thoroughly and reaches the following conclusions: "In the final analysis, ..., the problem that confronts us all is that of relating our experimental criteria to the criteria that are relevant to the use and operation of systems in the real world," (Chapanis, 1970, p. 345). Furthermore, "If we are to have a viable science and respectable technology we must develop and use techniques that are powerful alternatives to the typical laboratory experiment," (Chapanis, 1967, p. 576). Thus, regardless of how workload is measured, it must ultimately be directly relatable to such system criteria as safety, training requirements, convenience, comfort, and cost, among others. Ultimately, any workload assessment system should be able to provide alternatives in equipment design as well as in selection, training, and/or utilization of the operator to optimize the reliable functioning of the human component in man-machine systems.

CONCEPTUAL MODEL OF OPERATOR WORKLOAD

To further the applicability of workload assessment in crew system design, we have started a long-range research program at the Research Institute for Human Engineering (FAT) which has as its objective the systematic investigation of operator effort exerted relative to specifiable input loads and performance criteria. The approach to be used will iteratively combine analysis, experimentation, and digital simulation modeling to specify operator processing capacity and how the human operator will budget his available capacity to meet mission objectives in dynamic man-machine systems.

In order to be able to handle all the problem-relevant variables, we find it practical to divide the broad area of operator workload into three functionally relatable attributes: input load, operator effort, and work result, where:

> *Input Load* is operationally defined as a vector (L) of input data which must be transformed by the operator into a vector (P) of output data to satisfy a specified performance criterion function and/or to maintain a homeostatic operator state.
>
> *Operator Effort* (E) is operationally defined as the proportion of *processing capacity* (as determined by the time-

variant status of the operator state, and the contents of long- and short-term memories) which must be used to meet the *processing requirements* associated with transforming L into P.

Work Result is operationally defined as the data output vector (P) generated through the effort exerted by the human operator, which serves as input to other components of the man-machine-environment system and provides feedback on effort adequacy.

Generally speaking, input load is determined mainly by factors or events external to the human operator while operator effort is determined by factors or events internal to the human operator. There is thus no limit on the load with which an operator may have to deal. But, by virtue of the fact that the operator is a closed subsystem with a limited and fluctuating reservoir of available processing capacity, the effort which can be exerted to meet any load has certain specifiable boundaries. Viewed from this standpoint, the ultimate objective of operator workload research should be the development of techniques for reliable prediction of the effort a human operator can (or better, will) exert to meet specified levels of input load.

I have categorized the major sources of input load into three classes: environmental, situational, and procedural as can be seen in Table 2, which also contains examples of some of the factors subsumed under each category.

The course of events once an operator is faced with an input load is best explained with reference to Figure 2. The "readiness" of the operator to receive the various components of input load is determined by, what I call, the operator state. Under this rubric fall such factors as experience, motivation and set, physiological readiness, psychophysical

TABLE 2

SOURCES OF INPUT LOAD TO THE HUMAN OPERATOR

ENVIRONMENTAL	SITUATIONAL	PROCEDURAL
TEMPERATURE	CREWSTATION VOLUME	MISSION
HUMIDITY	DISPLAY CHARACTERISTICS	SOP'S
NOISE	CONTROL CHARACTERISTICS	TASK DESCRIPTION, SEQUENCING, AND ALTERNATIVES
VIBRATION	DISPLAY/CONTROL ARRANGEMENT	MISSION/TASK DURATION
ACCELERATION	LIFE SUPPORT PROVISIONS	INFORMATION AVAILABILITY
ILLUMINATION	VEHICLE DYNAMICS	BRIEFING AND INSTRUCTIONS
GEOPHYSICAL FACTORS		

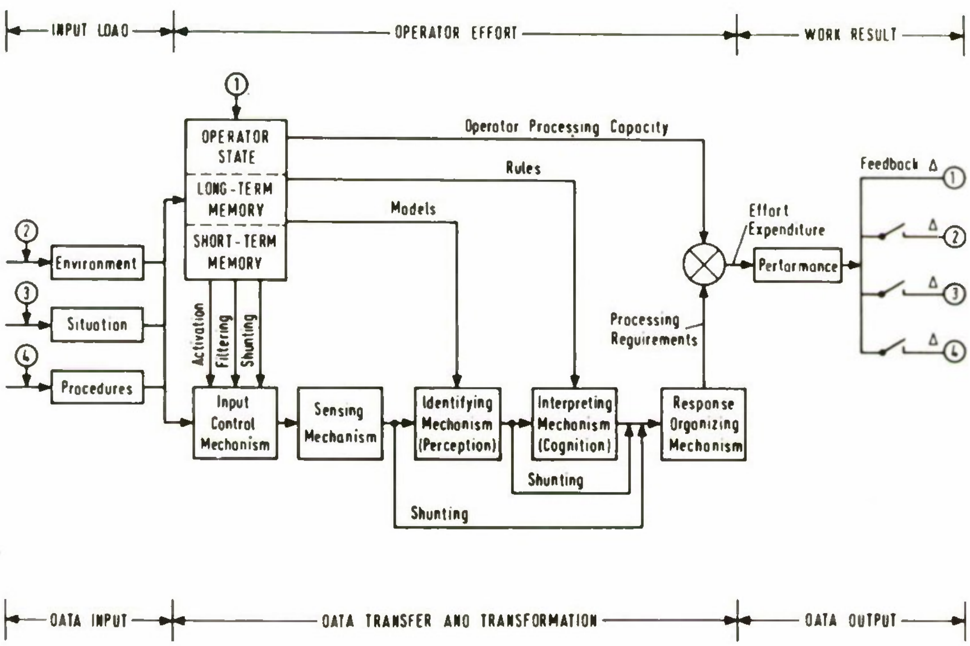

Figure 2. Conceptual structure of operator workload aspects.

factors, as well as the general background and personality of the operator. The input-load components combined with the operator state determine how the human functioning mechanisms (based on the concepts of Gagné (1962) will be activated to generate a work result of performance output. The activation and exercising of the human functioning mechanisms has associated processing requirements, and if the requirements exceed the capacity readily available as dictated by the operator state, performance will deteriorate or even cease to occur. Whatever the output, the operator state will certainly change as may some aspects of the input load (e.g., by self-induced procedure changes). Of course, the operator state, long-term and short-term memories are not really separate entities as drawn in Figure 2 but are interrelated to form an integrated as well as interacting source of processing capacity for meeting input load and as a self-regulating system for maintaining the homeostasis of the human operator.

Let us now take a closer look at the determinants of operator effort. As was already mentioned, the major determinant is the operator state (Table 3) some aspects of which may be continually changing (e.g., physiological readiness, experience, motivation and set) while others remain relatively stable (e.g., general background, attitude, personality, psychophysical factors).

It is hypothesized that the human operator will always strive to increase, or at least conserve, the amount of processing capacity available to him since the *relative* reduction (through effort expenditures) contributes to the ability for coping with unforeseeable future input loads. For example, the operator will perform if he decides he can learn something new by exerting the required effort. Thus, in any workload situation the human operator will attempt to minimize the effort required to meet these criteria. It should be pointed out that some of this striving for capacity conservation is overt (i.e., under the conscious control of the human) while other aspects are covert (e.g., the maintenance of homeostasis by the autonomic nervous system).

TABLE 3

ATTRIBUTES OF THE OPERATOR STATE

FLUCTUATING FACTORS	EXPERIENCE MOTIVATION AND SET PHYSIOLOGICAL READINESS ATTENTIVENESS
RELATIVELY STABLE FACTORS	PSYCHOPHYSICAL CHARACTERISTICS GENERAL BACKGROUND PERSONALITY ATTITUDE

The dynamic nature of effort expenditures needs to be investigated so that provisions can be made in crew system design for maintaining performance at criterion levels through effort conservation and/or capacity replenishment. Here I have followed Howitt's (1969) example who used three distinct time periods.

> *The immediate effort:* i.e., the operator effort exerted to handle an input load experienced over any given short period of time, e.g., take-off, descent, landing, or in airborne weapon systems the bombing run or attack phase.
>
> *The duty-cycle effort:* i.e., the cumulative effort exerted in meeting all the short-term input loads experienced during a mission or working day.
>
> *The long-term effort:* i.e., the effort produced over a sequence of missions or working days, which includes such factors as sleep and eating patterns and time zone changes.

Another determinant of operator effort is the content of long-term memory. The "models" of the real world, which have been acquired chiefly by a process of learning, are stored there, as are the "rules" for categorizing events into "if-then" relationships or "expected effects." The larger and more varied the number of models and rules, the larger will be the reservoir of processing capacity available for such tasks as decision making and problem solving requiring the use of the "interpretation function." Filtering conditions, by which the human operator is able to generate self-instructions or "strategies," are also stored in long-term memory as sources of processing capacity.

Finally, the content of the short-term memory as a buffer-storage for filtering and shunting conditions (provided through instructions) forms an additional determinant of operator effort.

WORKLOAD MEASUREMENT

Exact details as to the manner by which we will derive and use required measurement techniques within the context of the described conceptual model are still open to discussion, and I hope to be able to get some ideas from our workshop here. In general, we anticipate using an existing workload model and augmenting it with additional parameters and their interactions. Refinement of the concept shown in Figure 2 will be conducted analytically with subsequent derivation of requirements for experimentation.

Initially it should be possible to

specify input load in terms of information input and/or action requirements as partially available from task analyses, operational sequence diagrams and information flow charts. Parameters such as temperature, vibration, acceleration, which are not normally directly considered by current models, will be specified in addition to extending the consideration of factors impinging on the human operator.

To determine the operator processing capacity we will develop a diagnostic tool for assessment of the operator state by using current methods available from the domain of psychometric testing and by extrapolating data from the literature on stress, fatigue, learning, and attentiveness among others.

We will initially derive estimates of operator effort by combining objective performance data with some physiological measurements and subjective rating techniques. Data will be obtained during a series of man-in-the-loop simulation studies on the transition and landing phase of a V/STOL aircraft.

CONCLUSIONS

We need to get away from talking about "well trained, motivated, personable" human operators unless we can specify in quantitative terms what we mean by that. Hardware designers provide power supplies and calculate power consumption for their components, and, I think, we owe it to the well-being of our "human operator" component to at least try to do the same for him, by ascertaining the amount of effort a human operator needs to exert to meet overall mission objectives of the integrated man-machine system.

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APPLICATION OF MANUAL CONTROL/DISPLAY THEORY TO THE DEVELOPMENT OF FLIGHT DIRECTOR SYSTEMS FOR STOL AIRCRAFT

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Abstract: *Flight directors for conventional aircraft do not provide the pilot with adequate information to maintain satisfactory performance and control of a STOL aircraft during landing approach. Closed-loop pilot/flight-director/vehicle analyses point up the important vehicle factors and show how they influence a set of pilot-centered and guidance-and-control requirements. Typical vehicles include those that require both airspeed and flight path control as well as those that are speed stable and hence require only flight path control. In all cases, a direct lift capability utilized for glide path control is assumed to be the unique feature of the STOL aircraft. A two-axis longitudinal director system is then designed from the principles of manual control/display theory for application to an augmentor wing type STOL aircraft. Since the synthesis of a STOL lateral director system is similar to that of a CTOL system, only the necessary changes and manual control aspects are summarized. The paper concludes with moving-base simulation results which verify the design technique.*

INTRODUCTION

The function of a flight director system is: to combine into one instrument the various display and computation elements used by the pilot in performing a given task, thereby reducing scanning and sampling workload; and to provide an appropriate command which essentially permits single-loop control of a multiloop situation for each manipulator. This most general combination is illustrated by the functional block diagram of Figure 1.

A typical flight director display is shown in Figure 2. It has horizontal and vertical command bars as well as a lift command indication on the left side. The command elements form the basis for the pilot's control actions. In conventional aircraft there are only the two central command bars, one for column and one for wheel. For a STOL, however, attitude is not effective in changing the flight path; therefore, an additional command cue is necessary. This command is tailored for the dominant path controller--i.e., direct thrust, flaps, nozzle, etc.

The remaining elements of the display indicate the aircraft's absolute state relative to the external world. This "status" information includes an artificial horizon, glide slope and localizer deviation, radar altitude, and turn and slip indication.

The objective of the flight director design problem is to develop command displays from a combination of desired path, motion, and control quantities such that, when responded to by the pilot, the flight director will direct the vehicle onto the desired path in accordance with well-defined guidance and control requirements. In addition to the fundamental guidance requirements, the feedback quantities making up the "effective controlled element"--i.e., the vehicle-plus-flight-director dynamics, must be shaped,

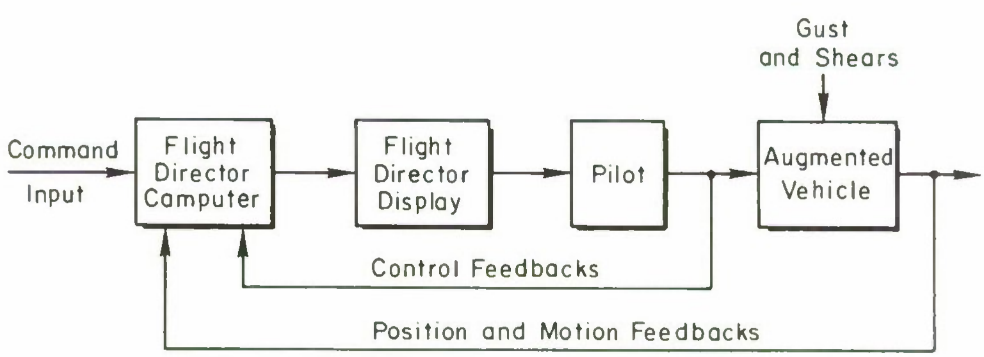


Figure 1. Flight director system elements.

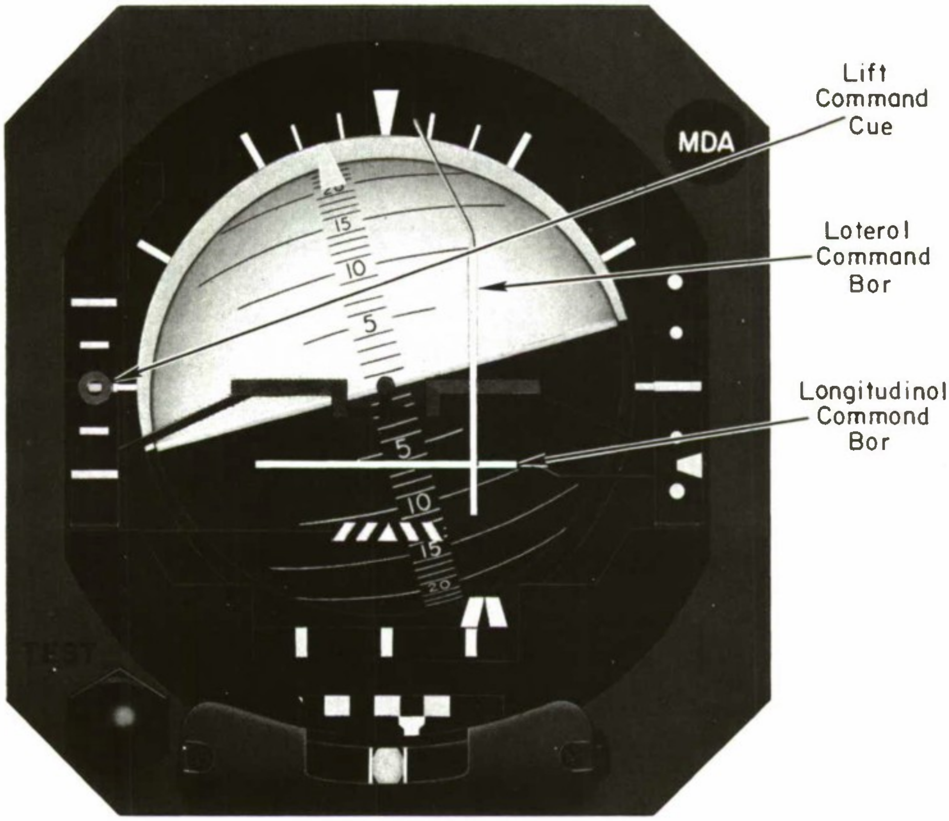


Figure 2. Flight director display.

filtered, and mixed in accordance with a set of pilot-centered requirements so that the pilot can close the flight director system loop with ease and efficiency.

The theory of manual control displays permits these pilot-centered requirements to be considered at the design stage along with the conventional guidance and control aspects rather than during the more extensive experimental stage, where development is guided solely by experience. The theory is based on the techniques, data, and models such as derived in McRuer (1965, 1967, 1969) for the analysis and design of control systems whose elements include man, display, and vehicle.

Although the situation depicted by Figure 1 could apply to almost all pilot control tasks, this paper concentrates on the low speed, steep angle landing approach problem unique to STOL vehicles. In this region STOL vehicles are usually on the backside of the power curve, have poor stability and response properties, and may have increased speed trim and control cross-coupling problems. Consequently, the feedback selection and the design of the director system are dependent on these key vehicle factors. To illustrate the effect of these factors on the longitudinal system, several different vehicles, including the XC-142, CH-53 helicopter, and C-8M augmenter wing aircraft are discussed.

In the lateral axis, the problem is primarily one of path control since there is only one controller available for the three degrees of freedom. However, heading control and crosswind approach techniques influence the design.

SYSTEM REQUIREMENTS

Manual or automatic approach control systems are designed to acquire and track a landing guidance beam. The fundamental requirements are that this be done in a stable and rapidly responding manner, despite the influence of both wind and noise disturbances. However, the manual approach situation has the added requirement that the approach control system be compatible with the human pilot. These requirements can thus be grouped into those that are:

- Pilot centered, or
- Fundamental guidance and control.

These requirements have been elaborated (Weir, 1971) for the longitudinal control of a conventional aircraft. In this section the

requirements have been expanded to cover STOL vehicles and generalized in their application to both longitudinal and lateral axes of control.

PILOT-CENTERED REQUIREMENTS

A proposed set of general pilot-centered requirements included the following:

- Minimize pilot workload,
- Insure motion harmony,
- Allow unattended operation, and
- Provide command bar consistency.

Some additional requirements may be needed for an augmented STOL aircraft with more than two command bars. These should include the following:

- Minimize scanning workload,
- Decouple controls,
- Minimize SAS failure transients, and
- Allow wing-low crosswind approaches.

Both sets of requirements are elaborated briefly below.

Equalization for minimum pilot workload. The desire to minimize pilot effort while retaining maximum system performance imposes requirements on the dynamic properties of the effective controlled element consisting of the vehicle plus flight director computer. As is very well known, the human pilot adapts his characteristics to compensate for the dynamic deficiencies of the effective controlled element. As part of this adaptation, he may be forced to develop low-frequency lead(s) and/or to adjust his gain precisely. When low-frequency lead is required of the pilot, a cost in pilot dynamic capacity is incurred (McRuer, 1965, 1967, 1969). This is reflected in increased effective time delay and equalization remnant. When there is more than one required fixation point, the remnant due to scanning is also increased (Allen, 1970). Increases in these quantities cause a deterioration in system performance and pilot ratings.

As a result of these human pilot properties, a design requirement should be that the effective control elements be constructed to:

- Require no low frequency lead equalization,
- Permit pilot loop closure over a wide range of gains, and
- Allow long dwell times on each instrument.

The flight director system meets this requirement when the effective controlled element approximates a pure integration, K/s, over the frequency range of pilot/director/vehicle system crossover. For this set of controlled element dynamics, the pilot response is approximately a gain plus time delay in the frequency region of control (near crossover). His time delay will be close to minimum, and the equalization remnant can be minimized with the proper choice of controlled element gain. Pilot lead generation requirements are small. In short, the key requirement is to adjust the weightings of the various motion feedbacks in the flight director computer so that the effective controlled element approximates the K/s form over a fairly broad frequency region.

Motion harmony. Motion harmony relates to the ways in which the various motions of the aircraft interrelate and how they affect the pilot. With a flight director present, the important cues are combined into a net "error" signal, which the pilot attempts to reduce to zero by manipulating the appropriate control. When this is done, the airframe motions generated by the pilot should be similar to those he experiences under VFR or other raw data control conditions.

Unattended operation. Accounting for other pilot workload and for periods of unattended operation is accomplished with effective controlled element amplitude ratio and phase characteristics that permit wide variations in pilot gain while retaining adequate gain and phase margins throughout the mid-frequency region. This implies that conditionally stable systems and feedback of beam integral are undesirable.

Command bar consistency. Some elements of a flight director display are intended to reproduce, instrumentally, portions of the external world which are sources of visual flight cues. These are referred to as the status information and, ideally, have a high degree of "face validity" with the outside world. The command signals must also have some aspects of face validity. But the cue here is different from status information in that the command signal is a *mixture* of control and vehicle motions so there is no corresponding real-world cue. However, some correspondence does exist between the command signal and the vehicle or control motions in each of several frequency bands. In each band, the flight director command may be dominated by a particular airplane motion or control quantity. So, even though there is no direct VFR cue which corresponds directly to the flight director command, the command signal must have some degree of consistency with the status elements on the display. Typically, this means the high-frequency motion relates to the vehicle attitude information and the low-frequency motion relates to the inertial path deviations.

Minimum scanning workload. Scanning is reduced by minimizing the number of director commands presented on the display. It is also

reduced by integrating the status elements, thus increasing effectiveness of parafoveal viewing; both reduce the scanning remnant. This is particularly important for STOL vehicles with more than two active control points.

Decoupled controls. For the case of more than one manipulator for each axis, the directors should be uniquely associated with their respective controllers. Primarily, this means that the feedbacks for each director are selected and weighted so that when the pilot uses a given manipulator he only generates a response on that respective director. The effective controlled element transfer functions for the other directors to that control input should be essentially zero.

Minimum SAS failure transients. Oue to the heavy stability augmentation necessary on many STOL vehicles, the flight director must provide a graceful degradation of system performance in the event of a SAS failure. This means that the pilot can sufficiently cope with the unexpected task with minimum re-adaptation.

Wing-low crosswind approach. Regulation against lateral disturbances can be accomplished by two methods: crab or wing-low (forward slip). Large conventional aircraft primarily use the crabbed approach, where the aircraft is pointed into the wind and sideslip is zero. However, the forward slip technique is particularly appropriate for STOL approaches because crab angles are relatively larger and therefore more significant as the approach speed decreases.

A summary of the above pilot-centered requirements and corresponding flight director implications is presented in Table 1.

GUIDANCE AND CONTROL REQUIREMENTS

In general, guidance and control requirements are independent of the type of vehicle. For an approach control system, the fundamental function is path control. Thus, the guidance law must provide for a stable, well-damped beam acquisition and subsequent beam following in the presence of wind disturbances and unusual initial conditions. More advanced systems, especially applicable to STOL aircraft, might also be required to follow higher order approach paths (e.g., dual angle or curved path). Additional requirements related to control include attitude regulation and damping, as well as the more fundamental vehicle requirements (i.e., control power, authority, etc.).

Table 2 summarizes the fundamental requirements for guidance and control. The degree to which each of these requirements can be satisfied is a function of the number of active control points as well as of the feedback quantities and equalization in the guidance law. For instance, in a conventional aircraft, lift control is dependent on attitude control; so in order to obtain path control, attitude regulation must suffer. However, with two active longitudinal controls, such as found in all low-speed STOL vehicles, the number of compromises can be reduced. This is especially important for higher order path following, which is impossible to satisfy ideally--i.e., with zero steady-state error, using elevator only.

TABLE 1

PILOT-CENTEREO REQUIREMENTS

REQUIREMENT	FLIGHT DIRECTOR IMPLICATIONS
REDUCED TIME OELAY MINIMUM REMNANT	K/S CONTROLLEO ELEMENT
BEST PILOT RATING	PROPER DISPLAY GAIN
UNATTENOEO OPERATION	NO INTEGRAL FEEOBACKS, OR CONOITIONALLY STABLE SYSTEMS
MOTION HARMONY	CLOSEO-LOOP CONTROL OOES NOT INDUCE ATTITUOES AND/OR ACCELERATIONS THAT ARE INCOMPATIBLE WITH OTHER FLIGHT MOOES
MINIMUM SCANNING WORKLOAO	MINIMIZE NUMBER OF DIRECTORS REQUIREO; MAXIMIZE EFFECTIVENESS OF PARAFOVEAL VIEWING
WING-LOW CROSSWING APPROACH TECHNIQUE	WASH OUT INNER-LOOP FEEOBACKS
DECOUPLEO CONTROLS	DECOUPLE AXES SO CONTROL OF ONE OIRECTOR OOES NOT EXCITE OTHERS
MINIMUM SAS FAILURE TRANSIENTS	MAINTAIN PROPER SAS-FLIGHT OIRECTOR FEEOBACK MIX

TABLE 2

GUIDANCE AND CONTROL REQUIREMENTS

PATH ACQUISITION PATH CONTROL PATH DAMPING HIGHER ORDER PATH FOLLOWING CAPABILITY
ATTITUDE REGULATION ATTITUOE DAMPING
GUST REGULATION WINO SHEAR REGULATION

IMPORTANT VEHICLE FACTORS

The development of a longitudinal flight director for STOL aircraft is very dependent on vehicle characteristics. This is true since at the low-speed STOL approach condition, appreciable lift is obtained from power (e.g., vectored thrust and engine inclination). Hence, the pilot control techniques and selection of flight director feedbacks will vary widely among STOL vehicles.

The primary problems that influence the longitudinal director design are:

- Operation on backside of power required curve,
- Poor speed trim characteristics, and
- Large control cross-coupling associated with insufficient attitude stiffness.

These are briefly discussed in the following paragraphs.

Flight path stability refers to the speed of the vehicle relative to the speed for maximum lift/drag ratio. Below the speed for maximum L/D, the vehicle is on the backside of the power required curve and attempts by the pilot to control altitude with the stick result in a static divergence. In the Mil Spec [MIL-F-8785B (ASG), 1971], this quantity is referred to as $d\gamma/du$, and, when negative, a decrease in airspeed will result in an increased rate of descent. With regard to flight director design, this implies that feedback of beam deviation to the stick director is no longer beneficial in the low-frequency region.

Speed trim problems influence the most effective control technique. These can be determined by inspecting the steady-state speed response ratio, u/θ, and the speed/flight path ratio, u/γ. The steady-state u/θ response ratio represents the change in speed that occurs when attitude is changed and held fixed. This ratio is listed in Table 3 for several types of aircraft. Note that for the XC-142, maximum values of u/θ are less than two kt/deg. This is about 50% of the value for a DC-8 in power approach and much less than that for a conventional helicopter. It should be mentioned that although the helicopter appears to have no dc gain, the perturbation equations would not be valid for large speed changes.

When attitude is held constant, the sensitivity of speed to thrust inputs is revealed from trim flight path versus speed curves. Vehicles with large X_u (i.e., trim drag) and small $X_{\delta_T}/Z_{\delta_T}$ ratio (i.e., large thrust line inclination) will exhibit a small speed change and large resultant flight path change when the thrust is changed. From Table 3 it can be seen that the XC-142 and B-941 should have good inherent speed control, whereas speed control augmentation for the helicopter is best accomplished with attitude. The DC-8 could use either power or attitude.

Control cross-coupling pertains to pitching moments due to life changes--i.e., throttle, collective, flaps, etc. Primarily, it has the detrimental effect of exciting attitude motions that the pilot must compensate for in the stick loop. This increases pilot workload to the point where he may have to lower his gain in the flight path to thrust, or lift, loop. Recent efforts in flight director design (Kelly, 1970) have tended to increase the attitude stabilization in order to decouple the modes and reduce pilot

TABLE 3

COMPARISON OF SPEED CONTROL PARAMETERS FOR VARIOUS AIRCRAFT

PARAMETER	XC-142 50 KT $\theta = 0$ $\gamma = -8°$	XC-142 80 KT $\theta = 2.5°$ $\gamma = -8°$	B-941 60 KT $\theta = -7°$ $\gamma = -7°$	CH-53 60 KT $\theta = 0$ $\gamma = -6°$	DC-8 135 KT $\theta = 0$ $\gamma = -3°$
STEADY-STATE SPEED/ ATTITUDE RATIO AT CONSTANT POWER $\left.\frac{u}{\theta}\right]_{DC}$	-2kt/deg	-1.4	-1.1	$-\infty$	-4.0
SPEED/FLIGHT PATH RATIO FOR THRUST INPUT AT CONSTANT ATTITUDE $\left.\frac{u}{\gamma}\right]_{\theta = \text{CONSTANT}}$	0.5 $\frac{kt}{deg}$	1.5	-0.13	9.0	6.2

workload. It also frees the stick director to incorporate speed or other command functions. However, high gain attitude systems have several drawbacks which include:

- Reduced beam deviation to thrust control bandwidth since lift due to angle of attack is not utilized,
- Increased gust sensitivity since the vehicle resists weathervaning into the gust, and
- Extensive pilot gain and lead adaptation may be required if the SAS were to fail. This could result in large transient motions.

Examples of various STOL vehicles that would require different flight director feedbacks include the deflected slipstream XC-142, a very speed-stable vehicle which can be configured to various degrees of flight path stability; the direct-life CH-53 helicopter, which has virtually no speed trimability and is on the backside at 60 kt; and the blown-flap C-8M augmenter wing aircraft which has three primary longitudinal controllers which are highly interactive. Table 4 lists the longitudinal characteristics of these vehicles that change the selection of feedback quantities.

The next section presents the details of exactly how the feedbacks are weighted.

LONGITUDINAL FLIGHT DIRECTOR SYNTHESIS

In this section the steps involved in the design process are set down and the details of an example design for the C-8M aircraft are presented.

DESIGN PROCESS

The first step in the design process is to determine the control structure. This is accomplished by pilot-vehicle analyses and by recommendations of test pilots who have participated in the simulation studies. For the C-8M the evolved control technique was to control airspeed with attitude and flight path

TABLE 4

FLIGHT DIRECTOR/VEHICLE INTERACTION

VEHICLE	LONGITUDINAL CHARACTERISTICS	FLIGHT DIRECTOR FEEDBACK
XC-142 80 KTS SAS-ON	GOOD SPEED TRIM FRONTSIDE GOOD PATH CONTROL WITH COLLECTIVE LITTLE CONTROL CROSS-COUPLING SUFFICIENT ATTITUDE SAS	*STICK:* ATTITUDE WASHED OUT BEAM DEVIATION *COLLECTIVE:* BEAM DEVIATION BEAM RATE
XC-142 50 KTS SAS-ON	GOOD SPEED TRIM BACKSIDE POOR FLIGHT PATH CONTROL WITH COLLECTIVE LARGE COLLECTIVE/ATTITUDE CROSS-COUPLING POOR ATTITUDE SAS	*STICK:* ATTITUDE *COLLECTIVE:* BEAM DEVIATION BEAM RATE
CH-53 60 KTS AFCS ON	POOR SPEED TRIM BACKSIDE GOOD FLIGHT PATH CONTROL WITH COLLECTIVE NO CONTROL CROSS-COUPLING	*STICK:* WASHED OUT ATTITUDE AIRSPEED *COLLECTIVE:* BEAM DEVIATION BEAM RATE
C-8A (AUGMENTOR WING) 60 KTS NO LONGITUDINAL SAS	POOR SPEED TRIM BACKSIDE LARGE CONTROL CROSS-COUPLING POOR FLIGHT PATH CONTROL WITH NOZZLE NO ATTITUDE STABILIZATION	*STICK:* WASHED OUT ATTITUDE ATTITUDE RATE BEAM RATE AIRSPEED *NOZZLE:* BEAM DEVIATION BEAM RATE WASHED OUT NOZZLE DISPLACEMENT

with nozzle position. Thrust was assumed held constant once established on the glidepath. This structure dictates the fundamental feedbacks to each director. All other feedbacks with non-zero steady-state values should be washed out.

The next step is to examine the manual loop closure estimates to determine approximate feedback gain ratios and lead requirements. Predicted pilot lead time constants greater than one second should be included in the director guidance law since this would constitute a major source of pilot opinion degradation. However, in order to preserve high-frequency command bar consistency, a 1/2 to 3/4 second lag is also required in conjunction with the lead equalization.

The selection of gain ratios is based on the form of the effective controlled element and command bar consistency (both pilot-centered requirements) and closed-loop responses (guidance and control requirements). Starting with estimated gains and lead equalization requirements from the manual control analysis, the effective controlled element frequency response for both directors is examined. Gain ratios are varied to obtain K/s-like response characteristics over a broad range of frequencies. The nozzle director response is also checked with the column director loop closed. Additional feedbacks may be added to this director signal to increase the response in the region of crossover.

The final step is to close the director loops and compare closed-loop responses and rms beam errors to various inputs for variations in feedback quantities and/or equalizations.

DETAILED DESIGN FOR C-8M

In the column director, airspeed is controlled via attitude. To avoid standoff errors between attitude and airspeed, the pitch attitude feedback is washed out. This washout should be as rapid as possible in order to minimize glidepath deviations in the presence of wind inputs. The use of beam rate, $\dot{d}$, feedback provides the basis for achieving a faster washout. This does not compromise the path damping and significantly improves the low-frequency windproofing. The resulting washout time constant is equal to the flight-path-to-attitude lag, T_{θ_2}.

We now look at the airspeed-to-attitude feedback weighting. The effects of various airspeed/attitude gain ratios can be seen by examination of the effective controlled element responses, FD_S/δ_S, shown in Figure 3. Notice that the smallest gain ratio, -0.005 rad/ft/sec, produces a very low dc gain, which means the director bar will always be wandering. The highest gain ratio, -0.02, has the least K/s-like response and largest phase dip near 0.4 rad/sec. A reasonable compromise is the -0.01 value. In all cases pilot lead would be anticipated near $1/T_{sp2}$ to extend the region of K/s-like response. If $1/T_{sp2}$ is high enough, this lead should not produce any degradation in pilot rating for the flight director task. However, the required lead can be reduced by using attitude rate feedback as shown in Figure 3. In this case, an associated display lag at 1-1/2 to 2 rad/sec is also necessary to maintain high-frequency command bar consistency.

The resulting gain and washout values are as follows:

$$K_\theta/K_{\dot{\theta}} = 1.0$$

$$K_{\dot{d}}/K_\theta = 0.01 \text{ rad/ft/sec } (\doteq \tfrac{1}{2} \text{ deg/ft/sec})$$

$$K_u/K_\theta = -0.01 \text{ rad/ft/sec } (\doteq 1 \text{ deg/kt})$$

$$1/T_{wo_\theta} = 0.35 \text{ rad/sec}$$

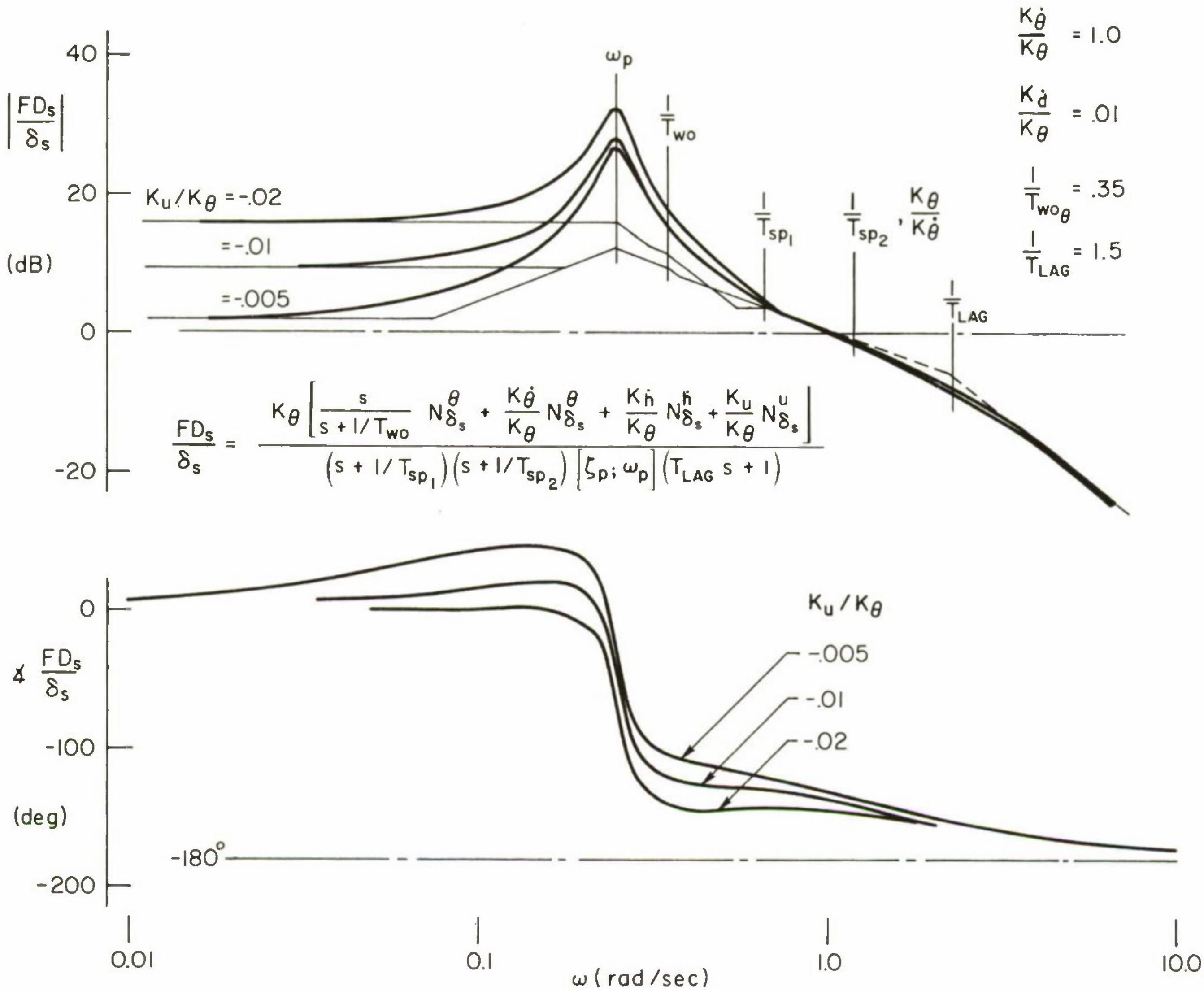
$$1/T_{LAG} = 1.5 \text{ rad/sec}$$

We can now turn attention to the nozzle director. From the manual loop closures it was determined that low-frequency lead equalization was required in the beam-deviation-to-nozzle loop. Therefore, the director signal should contain beam rate feedback in a ratio given by:

$$K_d/K_{\dot{d}} = 1/T_{LEAD} = 0.5 \text{ rad/sec}$$

Also, since the closed-loop short-period mode is about one rad/sec, the director bug will appear quite sluggish and will not reflect any mid- or high-frequency motions. This apparent lack of director response to rapid control inputs violates the requirement for command bar consistency, since the director should give a positive indication when the pilot moves the nozzle lever. This problem can be solved with an airspeed or control position feedback. However, airspeed feedback will reflect gust inputs and can be changed by other control inputs. Control position feedback is much more direct and less contaminated. However, this too has several drawbacks that must be accounted for. These include:

- High gains will make the display too sensitive to control movements, thus causing other essential feedbacks to be obscured,
- Undesirable feedback of pilot remnant may result. This problem is eliminated with lag filtering of the control position signal, and
- Aircraft trim changes will result in director standoff errors. This is avoided by washing out the feedback signal at low frequencies.



$$\frac{FD_s}{\delta_s} = \frac{K_\theta\left[\frac{s}{s+1/T_{wo}} N^{\theta}_{\delta_s} + \frac{K_{\dot\theta}}{K_\theta} N^{\theta}_{\delta_s} + \frac{K_{\dot h}}{K_\theta} N^{\dot h}_{\delta_s} + \frac{K_u}{K_\theta} N^{u}_{\delta_s}\right]}{\left(s+1/T_{sp_1}\right)\left(s+1/T_{sp_2}\right)\left[\zeta_p;\omega_p\right]\left(T_{LAG}\, s+1\right)}$$

Figure 3. Effective controlled element for stick as function of airspeed/attitude ratio.

Figure 4 shows the change in the high-frequency portions of the effective controlled element of the nozzle director as the gain ratio, $K_{\delta_N}/K_{\dot{d}}$, is increased from zero to 0.5 ft/sec/deg. This latter gain was selected to give a near continuous K/s-like response when used with a display lag of one second.

LATERAL FLIGHT DIRECTOR SYNTHESIS

The lateral synthesis is much more straightforward than the longitudinal director design process. This is because only *one* control, lateral stick, and therefore only *one* director bar are necessary. This implies that the vehicle possesses acceptable turning characteristics; that is, good feet-on-the-floor heading control or natural easily accomplished rudder coordination. Lateral director systems suggesting a compensatory pedal command signal are not considered desirable in light of pilot workload, which increases as the number of command displays increase. However, the rudder retains its conventional role as a coordination control, and the possibility of using a constant rudder bias in order to generate a partial wing-low crosswind approach is considered as part of the overall system requirements.

In general, the design procedure follows conventional control systems design procedures, since the bandwidth of the path mode response is well below the pilot/vehicle crossover frequency. Consequently the only difference between a lateral director for a STOL aircraft and one for conventional aircraft is that the gain of the path damping term should be decreased by the speed ratio, V_{STOL}/V_{CTOL}.

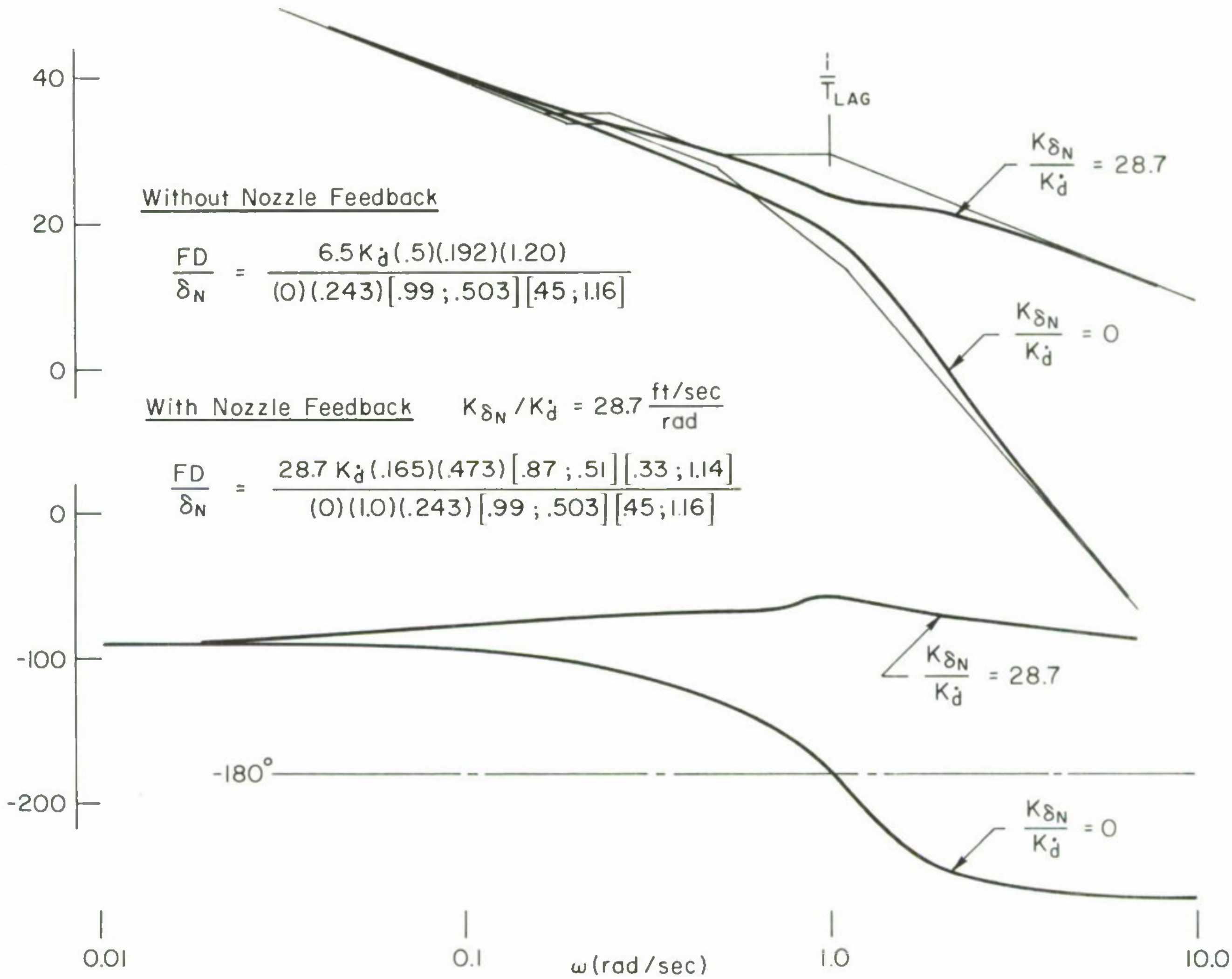


Figure 4. Effect of nozzle position feedback on nozzle effective controlled element.

The design procedure should also include the following items related to manual control.

1. Review vehicle characteristics to determine heading control problems. If necessary, use SAS to obtain a favorable location of the lateral flight path zeros--i.e., close to dutch roll poles.

2. Utilize integral pilot equalization in the closed-loop analysis if the spiral mode is at a higher frequency than the desired path mode--i.e., $Y_p = K_p[s + (1/T_{path})]/(s)$. This serves the same function as that of a parallel integrator operating on localizer deviation in an automatic system.

3. Set display gain so that the director reflects attitude motions at the attitude frequency. With this reference check, display consistency with other feedbacks. Too much low-frequency gain will force a reduction in the crossover frequency and hence a reduction in stability.

SIMULATION RESULTS

To verify the design techniques for both the longitudinal and lateral director systems, a short simulation program was run on the NASA Ames FSAA simulator.

The results showed marked improvements in pilot rating and tracking performance over the no-director case. Pilot ratings obtained from two pilots averaged two and three-fourths with the longitudinal director, as opposed to five and one-half without a longitudinal director. For the lateral director, the ratings improved from about four to one and one-half. Performance comparisons also showed marked

improvements over the no-director case. Of particular importance was the improved performance of the lateral system in crosswinds when lateral flight path angle feedback (derived from lateral acceleration independent of bank) was used for path damping instead of the conventional washed-out heading feedback. Table 5 summarizes the results.

CONCLUSIONS

A set of principles, functional requirements, and analytical procedures can be defined for specifying and designing STOL flight director systems. These permit the designer to select, equalize, and weight the director feedbacks analytically, given the (augmented) vehicle dynamics and a definition of the task. This involves some tradeoff between the basic guidance and control requirements and additional requirements based on human pilot considerations. These new concepts include the following:

- The effective director/vehicle controlled element should look like a K/s over a broad mid-frequency region,
- The director display should be consistent with status information--low-frequency and steady-state bar motions should be beam deviation, the mid-frequency deviations should reflect corresponding vehicle motions, and high-frequency motions should be attenuated,
- The compatibility of attitude, acceleration, and path motions has an important influence on pilot gain and system crossover frequency, and
- Scanning required to monitor status information will tend to reduce pilot gain, and this can be avoided by suitably integrating the status information on the display.

By using these principles and analytical techniques, the designer can: (1) analytically set up the flight director during the design stage; (2) determine the interaction of system components (e.g., feedbacks, SAS, vehicle, display, and pilot); (3) evaluate the tradeoff of guidance and control and pilot-centered requirements; (4) predict pilot opinions and closed-loop performance; and (5) plan the final optimization process involving actual pilots in simulation and flight test more expeditiously. The result is a more efficient design process and a demonstrably superior director/pilot/vehicle system.

ACKNOWLEDGMENTS

The initial research into STOL flight director systems applicable to the XC-142 and

TABLE 5

SIMULATION RESULTS

METRIC \ SYSTEM		NO FLIGHT DIRECTOR	WITH FLIGHT DIRECTOR
LONGITUDINAL PILOT RATING	PILOT 1	5	2½
	PILOT 2	5-7	3
LONGITUDINAL PERFORMANCE (1) (RMS DEG)	ε_{GS}	0.855	0.177
	θ	0.82	0.45
	δ_{COL}	0.37	0.21
LATERAL PILOT RATING	PILOT 1	4-4½	1½
	PILOT 2	3-4	1-2
LATERAL PERFORMANCE (2) (RMS DEG)	ε_{LOC}	0.216	0.042
	ϕ	3.48	1.05
	δ_{ω}	8.48	4.16

(1) MEASURED FROM 300 FT TO 50 FT ALTITUDE WITH 4 FPS RMS GUST INPUTS

(2) MEASURED FROM 300 FT TO 50 FT ALTITUDE WITH INCREASING AND DECREASING CROSSWIND SHEARS OF 4 KTS/100 FT STARTING AT 500 FT SUPERIMPOSED ON 4 FPS RMS GUSTS

CH-53 vehicles was sponsored by the Flight Deck Development Branch of the Air Force Flight Dynamics Laboratory for which the technical monitor was Capt. Robert A. Strahota. The application of the principles to the design, development, and simulation of the director system for the C-8M aircraft was sponsored by the Man-Machine Integration Branch and the Flight and Systems Research Branch of the NASA Ames Research Center. The NASA technical monitors were Everett Palmer and James Franklin, respectively.

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A STUDENT PILOT AUTOMATIC MONITORING SYSTEM

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Abstract: *In conceptualizing the Student Pilot Automatic Monitoring (SPAM) system, two key decisions were made. First, the system was not designed as a substitute for the human instructor pilot but as an aid to the instructor. Secondly, it was recognized that the system, if it was to be economically feasible, would be capable of scoring and grading only selected portions of the student pilot's overall flight performance. Based on these concepts, a series of studies was made of the methods to be used in developing the system and of the system hardware and software requirements. These studies have indicated that a practical, economical SPAM system can be developed. It has further been shown that implementation and integration of the SPAM system into undergraduate military pilot training will result in significant cost savings.*

INTRODUCTION

Studies of military pilot training were recently conducted by four independent organizations--Naval Air Training Command (1970), North American Rockwell (1971), Lockheed-California Company (1971), and Northrop Corporation (1971). One of the unanimous recommendations resulting from these studies was that efforts should be made to develop a system for automatically recording student pilot flight performance. The reason for developing a Student Pilot Automatic Monitoring system was stated by Persels (1970) as follows:

> "Considering the large number of variables that exist in almost any maneuver, he (the instructor pilot) may well miss one or more which are the key to the particular student's performance. It seems clear that a major improvement in training technique could be achieved if a record of the maneuvers could be made for later reference."

The ideal Student Pilot Automatic Monitoring (SPAM) system must be capable of recording a student pilot's flight performance in both an aircraft and in a simulator. In addition, the system must also include the hardware and software required to analyze, score, and grade the student's performance. Advances in solid state electronics, computers, displays, and digital recording techniques have now made the development of this type of system not only practical but economically desirable.

In recent years, many research programs have been conducted which have required the use of in-flight pilot performance recording techniques. Billings, at Ohio State University (1968), has made extensive use of onboard recording of aircraft systems and instrumentation outputs. Motion picture cameras and video recording techniques for pilot performance monitoring have been investigated by Isley for the U. S. Army (1968) and Valverde has done highly significant work for the Air Force (1970) in this same area. A fully instrumented T-37 is presently being used by the Air Force (Connelly, 1971) to collect pilot performance data.

In selecting a system for monitoring student pilot performance, there are certain requirements which must be met if a practical system is to be implemented. These include: ease of use, low cost, rapid data reduction, and application of the resulting data to both long- and short-term needs of the instructor and student.

To meet these requirements, a SPAM system must be more than a simple monitoring device. The total system must collect the required performance data, reduce this data to a usable format, aid the instructor pilot in quantitatively evaluating a student's performance, and provide easy access to the information necessary for an instructor pilot to manage the training and development of a student aviator.

SYSTEM OBJECTIVE

The primary objective of the Student Pilot Automatic Monitoring system is to aid the instructor pilot in quantitatively evaluating a student pilot's flight performance in an aircraft or simulator. The system also includes the equipment necessary for the instructor to manage and supervise the student aviator's training on an individualized basis. A secondary objective of the SPAM system is to improve training quality by facilitating the integration of the three training phases toward the achievement of training objectives.

Figure 1 illustrates the integration of the three classic areas of pilot training in order to achieve specific objectives. The shaded arrows indicate which areas are support areas and which areas dictate the training requirements. As stated by Havens (1970), "Academic training exists to serve flight training...." Military pilot training systems have as their goal the production of qualified aviators. Both academic training and simulator "flying" contribute to this goal, but the primary purpose of all these types of training is to teach people to fly airplanes. Therefore, the SPAM system was designed not as an independent system, but as an integral part of military pilot training which will enhance the integration of all aspects of pilot training.

SYSTEM CONCEPT

Student pilot performance may be monitored in many ways. In military pilot training, the student pilot's flight performance has traditionally been monitored and graded by an instructor pilot (IP). The real-time, subjective nature of the IP's judgment of the student's performance has long been the subject of debate. There are those who believe that modern technology should be applied in an effort to replace the IP with some type of infallible machine logic. The opposing point of view contends that the very nature of the flying task requires a unique set of attitudes, knowledge, and skill components which can only be demonstrated, taught, and critiqued by an instructor pilot.

Factual evaluations of the present military pilot training programs (North American Rockwell, 1971; Lockheed-California Company, 1971; Northrop Corporation, 1971) showed that an excellent job is presently being done by instructor pilots. At the same time, the IP's recognize their own limitations in attempting to quantitatively evaluate a student's performance. Therefore, the approach taken in designing the Student Pilot Automatic Monitoring system is based on the concept that the SPAM system is an aid to the IP and in essence provides him an extra pair of eyes to monitor performance parameters, an extra set of hands to write down and record data, and an auxiliary memory to store and recall information. This system will enable the instructor pilot to provide better instruction, closely supervise his student's training and at the same time, reducing training time and costs. This concept in turn defines the attributes that distinguish the SPAM system from other attempts to monitor pilot performance.

Instead of being only a monitoring device, the SPAM system is an instructor pilot

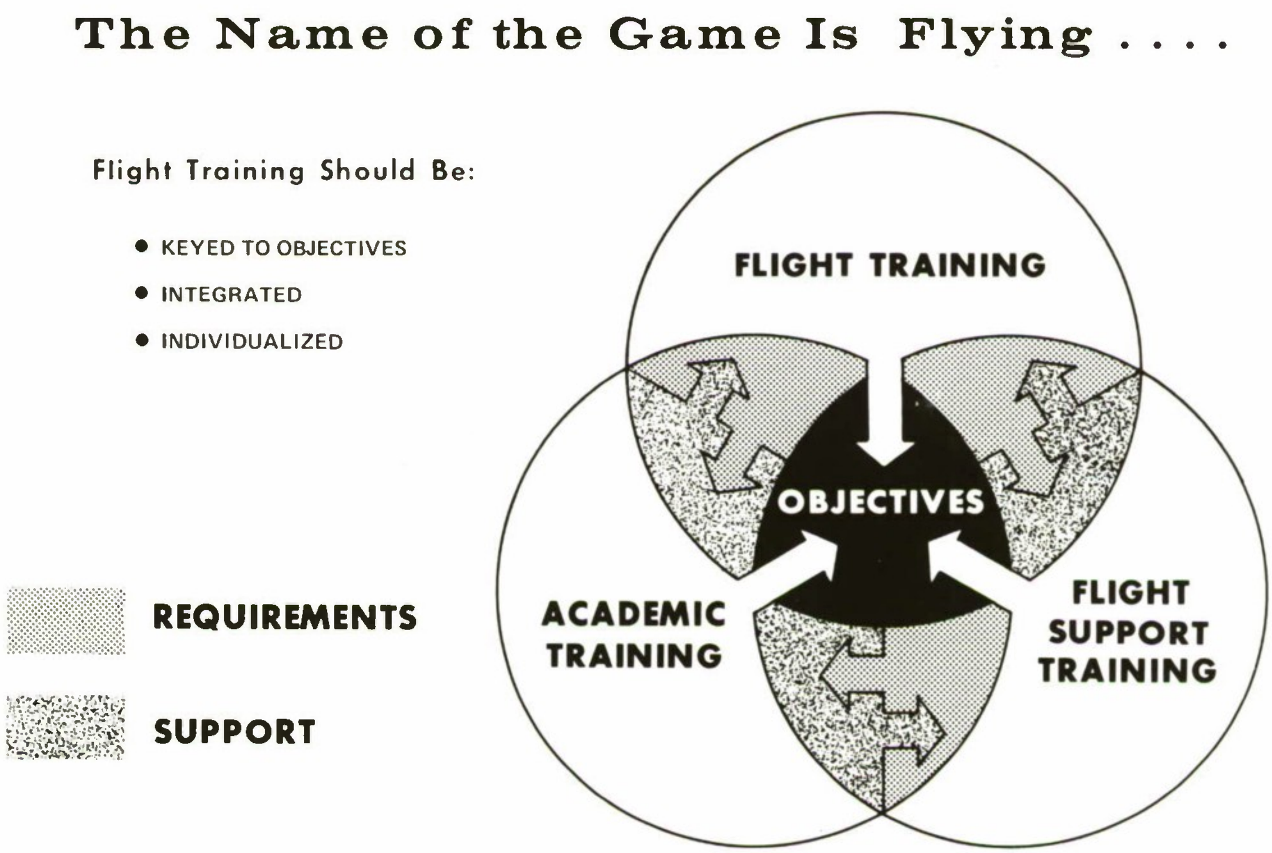

Figure 1. Integrated flight training keyed to objectives.

aid which will:

- Record selected portions of the student's flight performance for in-depth postflight analysis and quantitative scoring and grading,
- Free the instructor to concentrate on those qualitative portions of flight training where human judgment is indispensable,
- Aid the instructor pilot in training management,
- Produce an easily accessible quantitative and qualitative record of student performance, and
- Provide an information storage and retrieval capability for the instructor to use in performance diagnosis and training recommendations.

SYSTEM STUDIES

A series of studies was undertaken to investigate various aspects of the SPAM system. Initially a system analysis study was performed to identify both the tasks and problems involved in developing a SPAM system. Following this analysis, three coordinated studies were undertaken--they included investigations of hardware, software, and methods required to produce an effective SPAM system. The study results showed that the key portions of the SPAM system were well within the state of the art and could be developed and demonstrated within a short period of time. The system configuration, which was recommended as a result of these studies, is shown schematically in Figure 2.

As shown in Figure 2, the instructor pilot has access to all of the student's performance records. Through the use of a data base, which is an integral part of the SPAM system, the instructor can "tailor" training to the individual student's needs and assist him in obtaining the necessary attitudes, skills, and knowledge required for successful completion of flight training. When specific flight performance problems arise, the instructor has the option of selecting the least expensive training media (i.e., simulator, procedures trainer, or academic study) to correct the student's deficiencies prior to a repeat flight in the aircraft.

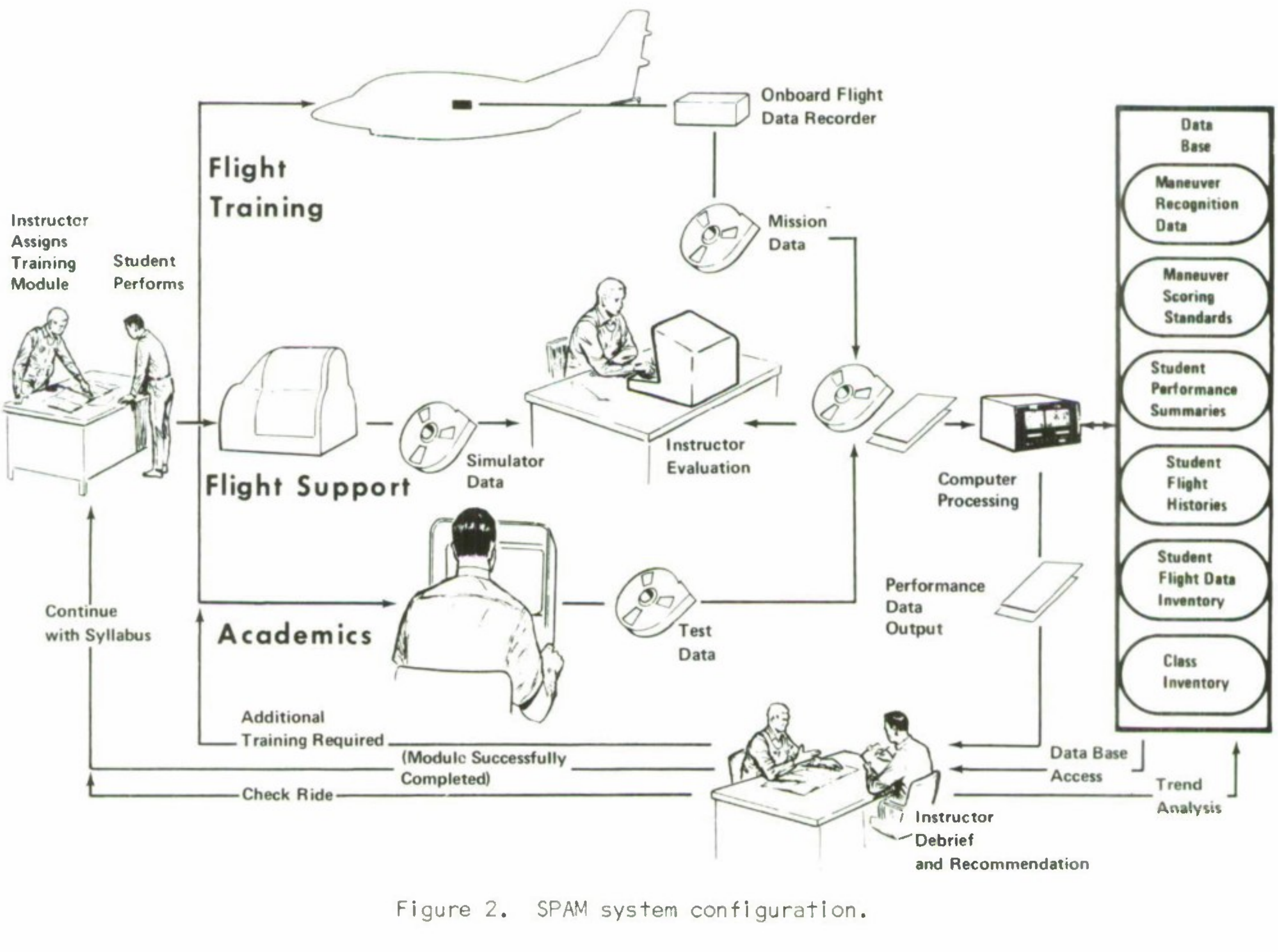

Figure 2. SPAM system configuration.

METHODS

An analysis of the Student Pilot Automatic Monitoring system showed the necessity for a method whereby the system software requirements could be determined. Chapter VII of CNABATRA's Manual, *Introduction to the Systems Approach to Naval Air Basic Training* (1968), presents detailed instructions for designing an instructional unit or increment. This method, a variation of which is shown in Figure 3, was originally developed for use in academic training. However, it is equally applicable to flight training when used by skilled instructor pilots. In exercising the systems software approach methodology, it became apparent that the basic problem was one of determining the correct measurement and scoring criteria. Several different approaches to this problem were investigated. A search of the literature and discussions with known experts in the field of performance measurement revealed two basic approaches to the problem. The first approach is referred to as Adaptive Mathematical Modeling and is discussed by Connelly (1967, 1971) and Knoop (1968). This method depends on a computer's "experience" with representative data. The program examines data; hypothesizes the "process effect"; examines human evaluation ratings with its own derived score; and adjusts as necessary to improve its approximation. Efforts in this area have had some success when applied to determining key parameters for specific maneuvers. However, adaptive Mathematical Modeling requires the collection and complex processing of enormous amounts of actual flight data. Thus far this has proven to be an extremely expensive and time-consuming process. A second, more straightforward approach has been selected to develop the SPAM system. This method involves the analysis of flight maneuvers, tasks, and phases of flight; selection of critical points throughout a maneuver; the application of instructor-furnished performance measurement and grading scales at each critical point; and validation of the critical points and measurement scales by actual tests. For use with the SPAM system, this method has been designated as "Critical Point Measurement."

Discussions with qualified IP's and perusal of the literature of flight instruction techniques, revealed that instructor pilots tend to monitor selected flight parameters at specific times throughout a maneuver or phase of flight. The IP then attempts to grade the student on his ability to hold these parameters within defined limits while performing the maneuver.

Problems with IP ratings have been discovered by Caro (1968) due to the fact that, although a standard error criteria may be used, IP's differ in the grade they assign for equivalent student performance. Recent work by Povenmire (1970) at the University of Illinois has shown that the use of standard performance measures in conjunction with standard grading scales results in an extremely high inter-instructor grade reliability, thus assuring that the student is given a "fair shake" regardless of the instructor pilot or check pilot with whom he rides. The Critical Point Measurement method is designed to use both standardized performance measures and standardized grading criteria. Measurement and criteria scales will be derived from analysis of the maneuvers as well as examination of actual performance data. On the basis of idealized performance recorded for a selected group of parameters, performance and grading scales will be developed using inputs by

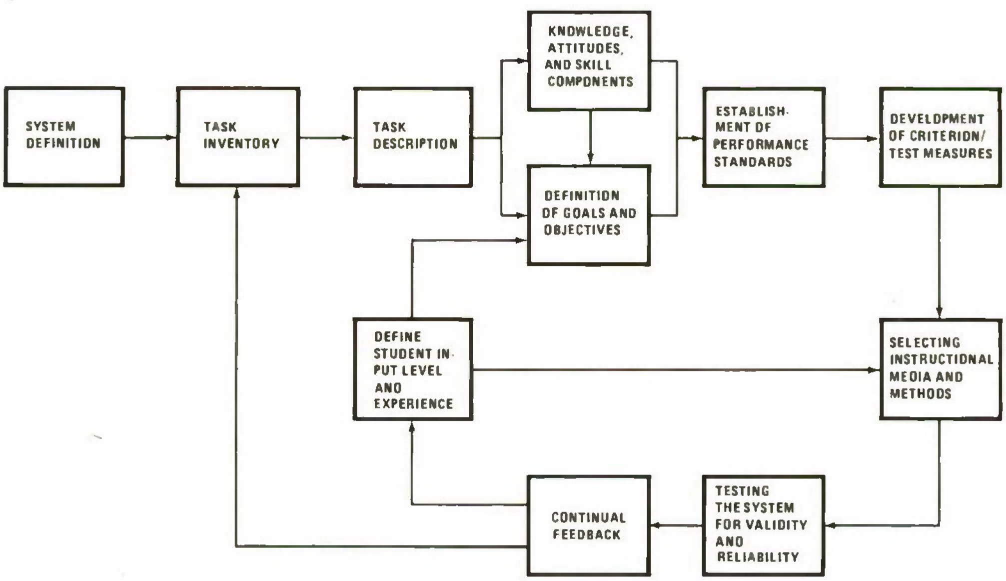

Figure 3. Schematic of the systems software approach.

qualified instructor pilots. The selected scale limits may vary according to the maneuver or phase of flight. For example, Figure 4 shows a series of candidate critical points throughout a loop. In the inverted position (CP-3) the flight syllabus gives the ideal airspeed as 140 KIAS. Ideal performance may therefore be designated at 140 ±5 knots. Airspeed deviations of ±10 or 20 knots may represent "average" and "below average" performance, respectively, while deviations in excess of ±20 knots are considered "unsatisfactory."

Excessively high airspeed is difficult to obtain over the top of the loop and is not considered dangerous. However, airspeeds below 100 knots are considered "dangerous" due to the possibility of entering an inverted spin. Extremely low airspeed may also require the instructor to override the controls to prevent further deterioration of the situation and could result in a failing ride for the student.

The syllabus also requires an airspeed of 140 knots on the downwind leg of a no-flap traffic pattern. In this situation, the allowable limits might be much more stringent than in a loop due to the ease with which airspeed can be controlled in this phase of flight. On the downwind leg, airspeed deviations of three to five knots may be considered average and deviations in excess of ±10 knots might be considered "unsatisfactory." Deviations in excess of ±20 knots might be considered "dangerous" because deviations of this magnitude may indicate a complete lack of alertness on the part of the student. The previously quoted limits do not represent exact scoring criteria but are given as representative of the process used in determining the scoring and grading scales.

Identification of critical points in a maneuver also requires the selection of key parameters from which performance may be scored. The performance parameters (Table 1) for use with the critical point measurement method were selected on the basis of information derived from special studies, a review of the literature, and discussions with specialists in aviation research. In selecting performance parameters, two important criteria were used. First, the parameters selected must be easily and inexpensively recorded onboard the aircraft, and second, exact information concerning these parameters must be easily available to the student while performing the required maneuver.

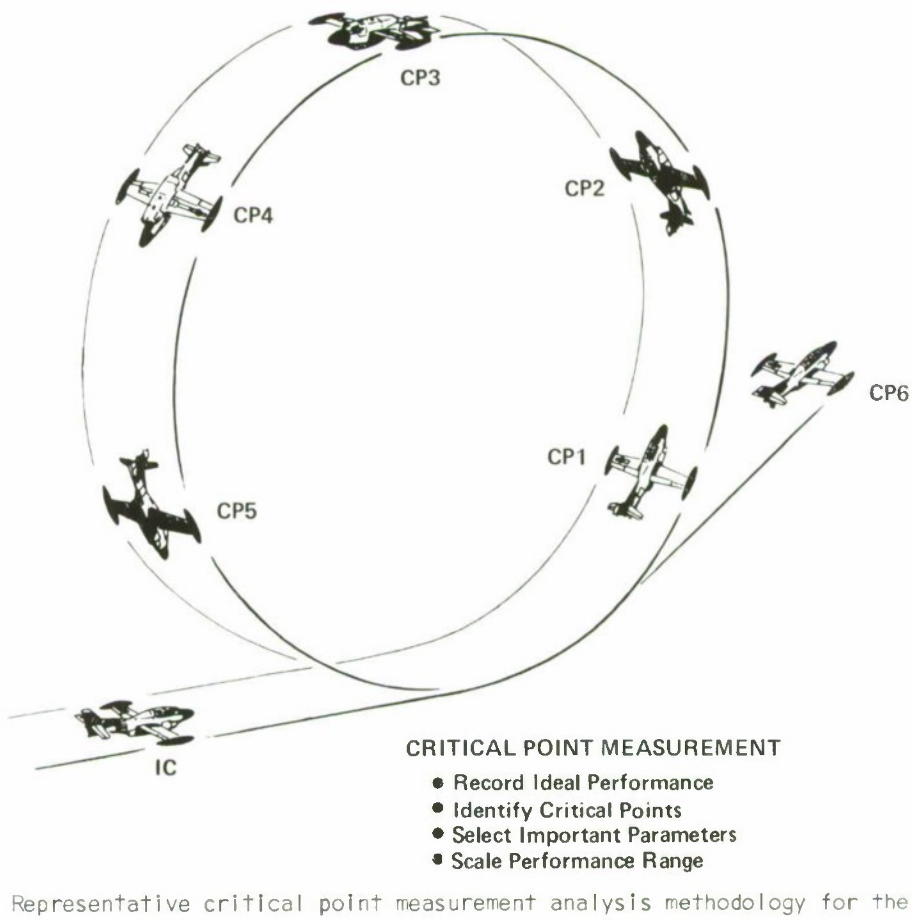

Figure 4. Representative critical point measurement analysis methodology for the loop.

TABLE 1

PARAMETERS TO BE RECORDED FOR STUDENT PILOT AUTOMATIC MONITORING SYSTEM

PARAMETER (VARIABLE DATA)	RANGE	RESOLUTION	NO. ELEMENTS	BIT LEVEL
AIRSPEED	50 TO 500 KNOTS	1.0 KNOT	450	2^9
ALTITUDE	0 TO 40,000 FEET	10 FEET	4000	2^{12}
VERTICAL VELOCITY	0 TO 6000 FT/MIN	10 FEET	600	2^{10}
HEADING	0 TO 360 DEGREES	0.5 DEGREE	720	2^{10}
PITCH ANGLE	±82 DEGREES	0.5 DEGREE	328	2^9
ROLL ANGLE	360 DEGREES	0.5 DEGREE	720	2^{10}
"G" LOADING	-2.0 TO +6.0 Gs	0.1 G	80	2^7
PITCH RATE	±0 TO 30 DEG/SEC	0.5 DEG/SEC	120	2^7
ROLL RATE	±0 TO 130 DEG/SEC	0.5 DEG/SEC	520	2^{10}
ANGLE OF ATTACK	0 TO 30 DEGREES	0.5 DEGREE	60	2^6
TACAN BEARING	360 DEGREES	1.0 DEGREE	360	2^9
DME DISTANCE	0 TO 200 MILES	.25 MILE	800	2^{10}
TIME	HOURS 0 TO 23	INTEGER	24	2^5
	MINUTES 0 TO 59	INTEGER	60	2^6
	SECONDS 0.0 TO 59.9	INTEGER	600	2^{10}

HARDWARE

The hardware required to support the SPAM system was divided into two categories--airborne and ground based. Figure 5 is a schematic of the airborne equipment. This equipment consists of: (1) the sensors, which provide the outputs for the scoring and grading of selected performance measurement parameters; and (2) the digital recorder and its associated equipment which will provide data for postflight performance analysis using the ground-based information processing, storage and retrieval subsystem.

Sensors for each flight parameter were selected to meet the data processing range and resolution requirements. Whenever possible, existing data sources, already part of the aircraft system, were used with the addition of A to D converters to compatibility with the onboard recorder. Location of this equipment onboard an aircraft is illustrated in Figure 6.

Major advances in digital recording systems such as the availability of small, inexpensive, digital tape cassettes, contributed greatly to the feasibility of the SPAM system concept. Digital tape cassettes provide easy transportation to and from the aircraft and reduce ground processing time. It is estimated that data from a typical one and one-half-hour training flight can be processed and the information ready for the instructor's use in postflight debriefing within a maximum of ten minutes after completion of flight.

The flight performance parameters to be monitored onboard the aircraft are all available in the simulators presently being procured to support pilot training. It is estimated that integration of the SPAM system with these simulators will require minor engineering modifications. As the SPAM program proceeds, data derived from the prototype system will provide the necessary information for an exact quantitative comparison between flight performance in the aircraft and performance of the same maneuvers or phases of flight in the simulator.

The ground-based, data-reduction and processing hardware is illustrated in Figure 7. This equipment consists of a cassette reader, instructor's terminal, (input-output display console), electrostatic printer, and a computer and disc memory unit. The ground-based equipment was sized for use by individual instructors in the flight room.

SOFTWARE

The SPAM system software consists of the programming required for: (1) ground-based data reduction and analysis; (2) hard copy printout; (3) display readout; and (4) data base storage and retrieval programming. Figure 8 illustrates the ground-based, data-processing subsystem. It includes an automated scoring program to process flight data and produce objective, standardized, performance

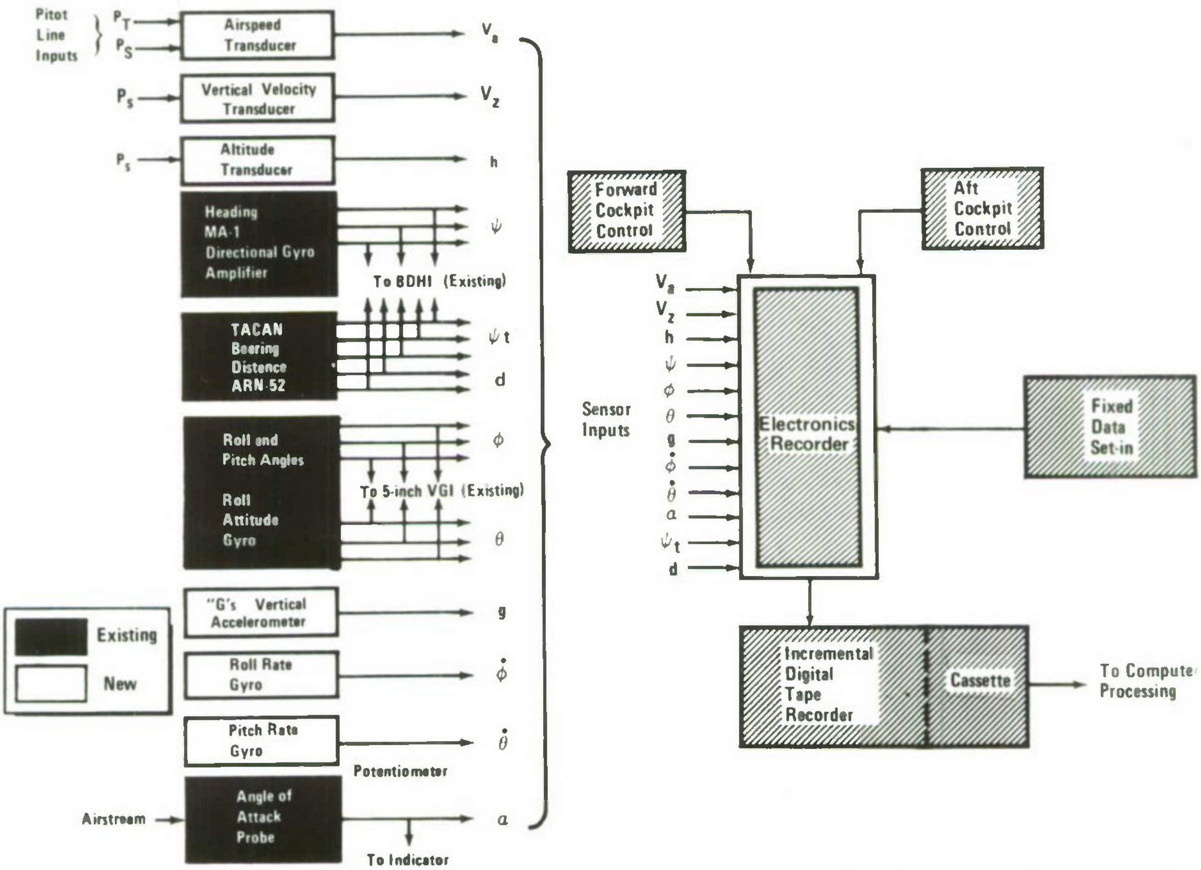

Figure 5. Airborne equipment for sensing, displaying, and recording flight performance data.

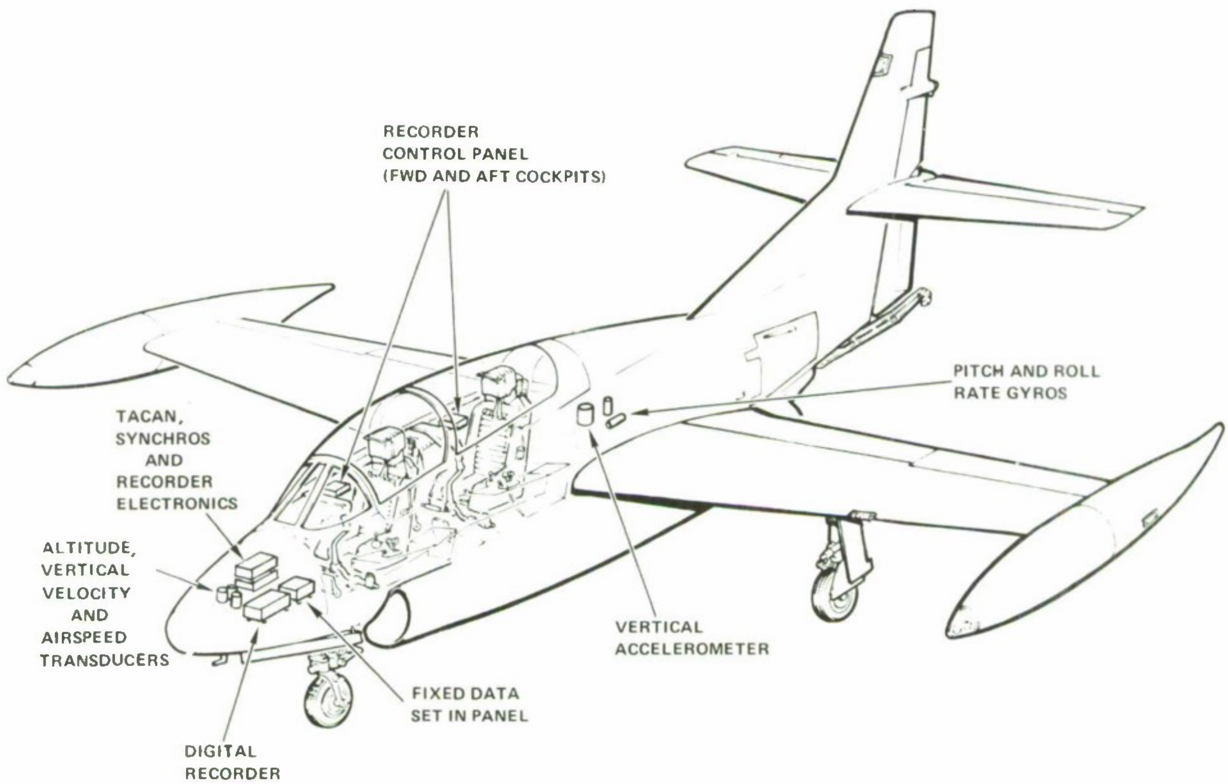

Figure 6. SPAM system sensor and recording equipment locations.

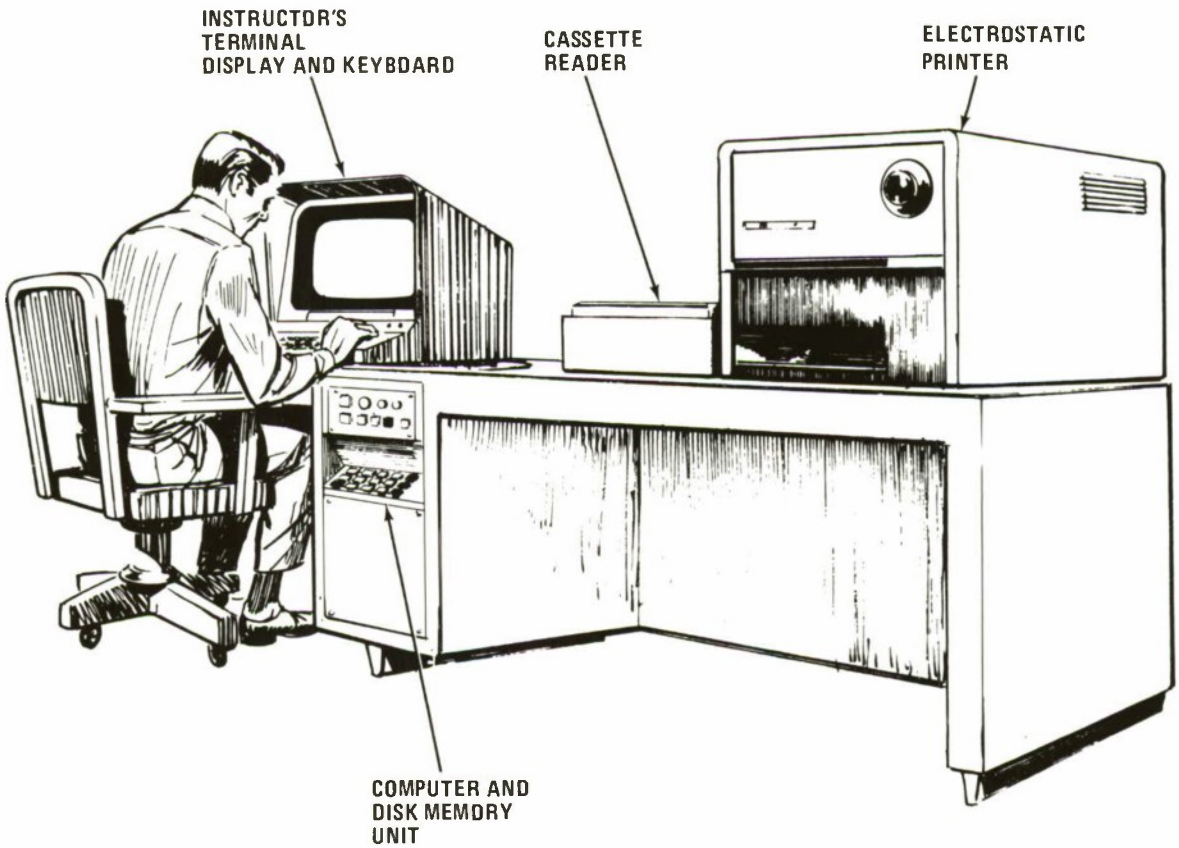

Figure 7. Ground-based data processing equipment.

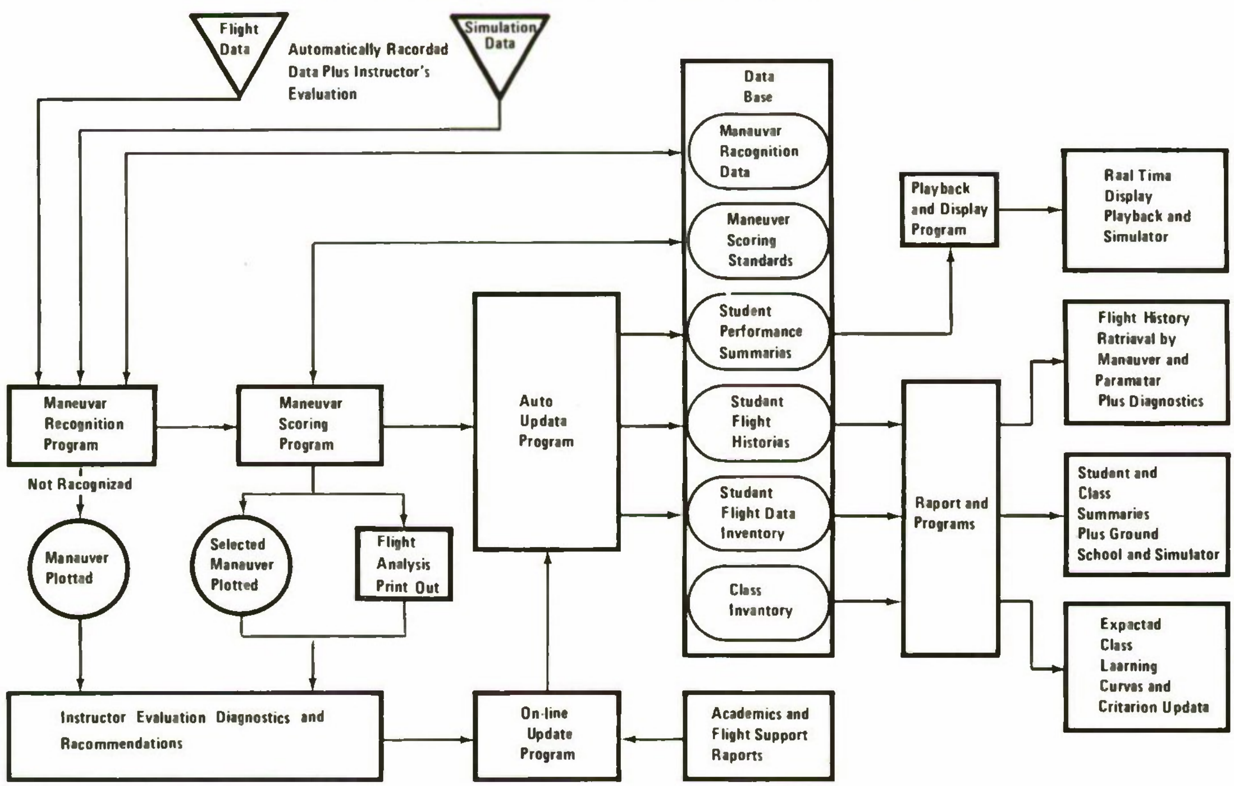

Figure 8. Ground-based data processing subsystem.

scores. Both displayed data and hard-copy printouts of performance scores will be available for the instructor to use in debriefing his students. Summary data outputs, compatible with existing data reporting systems, are also available.

The scoring program will identify points at which the student's performance deviates from predefined criteria and plot maneuver profiles of selected parameters.

The data base, together with its supporting storage and retrieval programs, will assist the IP in making recommendations for individualized training. Data will be stored in a form that will provide ready access to a student's complete flight training record. Additional software may be added as necessary for storage of simulator performance data and academic grades. Summaries and reports may also be provided on a regularly scheduled basis. With appropriate simulator modifications, it would also be possible to "replay" an actual flight in the simulator using the SPAM system.

FLIGHT TRAINING COST REDUCTIONS

The SPAM system will not only increase the efficiency of pilot training, but large cost savings are possible by using the system to reduce total training time and by emphasizing the instructor pilot's role as a training manager. A comparison of the actual training hours flown per student, versus the programmed syllabus hours, for one branch of the service, has shown that the programmed 120 hours of basic jet training actually require an average of over 158 hours per student (North American Rockwell, 1971). The total cost of training one basic jet student has been computed at approximately $300 per syllabus hour. (This cost does not include the cost of the aircraft or the base operating costs.) Assuming a load of 1500 students per year in basic jet training, a reduction of one syllabus hour per student results in a savings of approximately $45,000 per year.

Many of the extra hours presently flown in excess of the syllabus requirements are caused by weather delays, which require rechecks, or are due to repeats of partially completed missions for reasons beyond the instructor's control. However, many of these extra hours are also flown because of difficulties or problems encountered by the student, resulting in down flights and repeat rides. Through use of the SPAM system, the instructor will be better able to identify student problems and recommend corrective action before an unsatisfactory ride occurs. In addition, the instructor will have the option of selecting less expensive training modes for correction of flight deficiencies.

The SPAM system data recording capability, in essence, makes every flight a check ride. Storage and retrieval of quantitative flight performance data permits a check pilot to review a student's complete flight history and combine two or more stages in a single check, or eliminate some check rides altogether. Also, using the SPAM system to review a student's flight history, the check pilot is able to concentrate on those portions of a stage where the student has experienced problems.

Another possibility for reducing total training hours is the implementation of student "buddy rides" (two students flying together), during instrument practice flights. One student (acting as safety pilot in the front seat) would have the opportunity to perform a takeoff and landing and also increase his knowledge of instrument flight by observing the procedures and techniques of the student flying instruments in the back seat. The instructor could evaluate both students' performance, using the recorded flight data.

By summing the possible reductions in training hours, a potential savings of several million dollars per year is possible. It is important to note that these would be recurring savings which would be realized year after year.

In addition, the trend analysis capability of the SPAM system becomes a powerful tool for identification of failing students. If analysis of a student's record indicates a small probability of success, he can be eliminated early. On the other hand, if the trend analysis indicates a specific problem, individualized instruction can be given, thus preventing later elimination from training. In either case, large dollar savings would result. These cost savings cannot be accurately quantified; however, they represent potentially large amounts.

In the hands of skilled instructor pilots and operations personnel, new methods and techniques for using the SPAM system will undoubtedly be devised. The years of research and technological efforts applied to instrument flying resulted in advances from the old "needle, ball, and airspeed" days to the present "attitude instrument" system. The ability of the SPAM system to monitor and record many flight parameters opens the door to TRUE PRECISION FLYING, not only in instrument flight, but throughout all phases of flight training. The ultimate impact of this type of training will eventually be found in the production of consistently superior military aviators.

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PRACTICAL PROBLEMS IN USING HUMAN OPERATOR PERFORMANCE DATA

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Abstract: *During the past two years, human performance has been investigated within two generic system contexts--manually controlled antiaircraft artillery against high performance aircraft and air-to-air combat in air superiority fighters. The broad objective of this research was to assess the effectiveness of proposed air weapon systems, combat strategies, and countermeasures techniques. In meeting these objectives, it was necessary to address many problems associated with the use of human operator performance data. This paper describes six problem areas considered relevant for this workshop: system versus operator effectiveness, performance feedback, attrition modeling, stress tolerance, human operator identification, and system simulation.*

During the last two years, our group has gathered a considerable amount of data concerning the human as a weapon system controller. The experiments have mainly been concerned with two generic systems: manually controlled anti-aircraft artillery against high performance aircraft and terminal air-to-air combat in air superiority fighters. In each case, systems applied questions were addressed. In all, over 10,000 runs including over 100,000,000 data points have been analyzed.

In all cases, the effectiveness of the weapon system (in both cases aircraft attrition) was computed along with subject-related scores such as RMS error, error variance, and training feedback "hit scores." Performance of human operated anti-aircraft artillery (AAA) was obtained primarily to assess the effectiveness of specific countermeasures designed in this laboratory. A secondary goal was to provide real-time tracking data for use in attrition modeling. Air-to-air combat effectiveness was measured to provide estimates of system effectiveness in and after high acceleration maneuvers.

These programs have many common ties. They both involve: (1) the effect of stress on the human operator; (2) the analysis of manned weapon system effectiveness; (3) the identification of human control parameters for performance prediction; (4) simulation of weapon systems and combat scenario; (5) physiological mechanisms causing performance decrements due to the stresses unknown; and (6) the objective of applying to many weapon systems. Because of this commonality, the applications will be discussed with little further reference to the actual sources.

The major problem areas attacked by our work of interest to this section are: (1) system effectiveness and subject effectiveness; (2) effectiveness feedback and subject optimization; (3) attrition modeling as performance data; (4) stress tolerance, prediction or notation; (5) human operator identification state of the art; (6) system simulation; (7) difficulties with current identification techniques such as multiple input controller, manual control with decision points, discrete task identification, and task difficulty metric.

SYSTEM EFFECTIVENESS

The measurement of human performance in terms of system effectiveness was dictated by project goals. In the end, tradeoff analyses had to be made in terms of where and how to use new aircraft and which countermeasures should stay on an aircraft and which should come off. Therefore, measures of survivability had to be made. In the process of evolving effectiveness measures, implementing interim feedback scores, deriving on-line attrition models, and measuring human contribution to the system, we made some interesting observations.

In almost all weapon configurations and real-world forcing functions (target trajectory), there is no correlation between tracking error variance and hits on target. This point becomes interesting when one considers that almost all performance data taken on tracking systems to evaluate displays, controls, stress effects, subject training, etc., use tracking error metrics. In many situations, a system change can bring about an increase in hits with a concomitant increase in mean squared error. It was further noted that the error distribution is non-stationary and when taken in stationary pieces is non-gaussian with a non-zero mean, defeating all of the standard assumptions for tracking models.

EFFECTIVENESS FEEDBACK

Another difficulty of some experimentation is that the ultimate performance of the system and the metrics upon which a subject's performance will be judged are not available to the subject as they would be in the real world. It is a difficult procedure to implement on-line system performance with ballistic and vulnerability models including such niceties as fire control computers, ammunition stores, and such. Much of the success in finding man's performance lies in this ability, however. When the human operator feeds tracking information into a fire predictor (the case with most weapons), he must not only provide accurate tracking data, he must also provide it for a specific length of time and with specific spectral content. Stress often affects these secondary constraints and the effects are missed by error analysis. Further system performance feedback allows optimization for the rational cost function and decreases the correlation between error and performance.

ATTRITION MODELS

In the end, effectiveness models such as performance data solve another problem--that of "how much error makes a difference." As seen, using a change in the probability of hit on target is much better than a change in mean squared error because the two may not be related, but if hit probability is already high, a large change may still make no difference to survivability. With the system goals being so well defined, one might as well measure with respect to these goals and give the change in the number of planes shot down or probability of survival.

STRESS TOLERANCE

One of the strong points of a human controller is his ability to adapt control strategy. Not only will he pick a control to minimize error but will change to various environments, forcing functions, plant dynamics, or noise injection to maintain a small error (or other performance criteria). This makes the human's response to stress extremely difficult to study by means of error observation only. In an experiment on stress effects, one would desire to test effects of many levels of stress against a performance metric. In this situation, the usual response of the subject is to adapt at an extremely high level, such that system error remains relatively stable until such a point as the entire system fails catastrophically. At this time, the only observation that can be made is that system error did change catastrophically and to formulate a tolerance envelope. The tolerance envelope, when averaged across vast subject variability, motivational differences, training and circadian effects, can produce outer design limits. However, its usefulness in predicting failure or performance change and its usefulness in modeling the interactive effects of sequential or concomitant stresses is marginal. In this situation, one of the techniques that is used in this laboratory is that of human operator identification. This is possible where an easy identifiable input and output from a control task is available. Using these techniques, changes in the operator's control strategy can be noted and followed as the stress progresses. Also measurement can be made of maximum values of these parameters under any given environmental and motivational situation. With the progression of parameter value with stress and the knowledge of the final values obtainable, prediction of performance in stress is possible.

HUMAN OPERATOR IDENTIFICATION

In the last few years, techniques for identifying systems have been improved to the point where application to the human operator is now possible. Within the last year, in our laboratory and under contract, new techniques have been put into effect that allow identification of 80 to 90 percent of a human operator as a linear system in the presence of predictable inputs, complex plant dynamics, and injected noise. Further, techniques of gradient search and shifting between identification algorithms within one identification scheme have shortened identification time for even complex systems to that extremely practical with large computers. This advance in the state of the art now makes possible the observation of mechanisms in performance degradation, allowing these mechanisms to be exploited both in the production of countermeasures and in the production of performance-assisting techniques such as the development of new displays and controls.

SYSTEMS SIMULATION

One of the difficulties of this type of research has been the scale under which large systems simulations must take place. It is unusual to find large-scale simulation and system effectiveness metric implementation only in large industry and government laboratories concerned exclusively with applied research and it is usual to find investigation of simulation techniques only in laboratories where the production of such simulation is not possible because of lack of funds. In large-scale space validity simulations, it is possible to find a great many facets of a real-world system simulated without making even one test to ascertain the necessity for the simulation. In some of our laboratory's early research on simulating certain foreign weapons, the necessity for simulation existed before we had collected adequate information concerning the devices. In this situation, it was necessary to test for sensitivity many factors of

weapon system control. Some of the most sensitive variables were apparent angular velocity which entails the target velocity, range, offset, magnification, field of view, method of weapon control, and environmental forces on the man. Some of the least sensitive variables were plant dynamics, mechanical configuration, and illuminants.

DIFFICULTIES WITH CURRENT IDENTIFICATION TECHNIQUES

Currently identification techniques have been applied to practical problems having only one input and one output. It is indeed possible to extend the theory to multiple input controllers. There is no reason to believe at this time that the same techniques won't be directly applicable. However, this will be a new world. In addition, in a broader application, it would be extremely valuable to be able to identify the manual controller with intermixed discrete tasks. Again, theory is available to handle this situation, however, application must lie in the future. No description can be made of the various sources through which man is getting information on the state of his weapon system. This includes simple scanning of an instrument panel to the feeling of acceleration and force components. Further, no useful measure of difficulty exists--i.e., it is not possible at present to relate any of the task difficulty metrics to the effectiveness of a weapon system. For example, at this time, no one can predict how many remotely piloted vehicles one operator can control in any stage of a mission. Unfortunately, these aspects of identification theory are in the exploratory stage and will remain so for at least some small amount of time.

CREW STATION DESIGN USING COMPUTER GRAPHICS

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Abstract: *This paper gives a brief description of a computer program written by the Air Force Flight Dynamics Laboratory to generate external vision plots for an aircraft cockpit. The program involves the use of a Control Data Corporation Digigraphics Display console which allows the designer to see a visibility plot on a CRT screen and to interact with the computer to change the design eye point or the size and/or position of the "windows." An example is presented which illustrates a specific application of the program.*

INTRODUCTION

This paper discusses the background and related development efforts which led to the production of the motion picture "Computer Graphics" which serves as the conference presentation. This movie was produced by Capt. Frank Adinolfi, Jr., of the 1361st Photographic Squadron/MAC located at Wright-Patterson Air Force Base, Ohio. The basic purpose in making the film was twofold. First, it was designed to show the capabilities of computer graphics and how they work, and second, it was to make crew station design engineers aware of a specific program written to design the external vision for an aircraft cockpit. This movie is available for additional showings upon request to the Air Force Flight Dynamics Laboratory (FER), Wright-Patterson AFB, Ohio.

COMPUTER GRAPHICS PROGRAM

BACKGROUND

The basic concept of computer graphics is to interact with the computer by using some type of display scope. Normal digital computer programs are written to compute in sequence. That is, the computer reads the first instruction, performs it, then takes the second, the third, etc. The computer graphics program is written in the same manner, however, there are various points in the program where the computer reaches a graphical instruction and it stops computing. Depending on the type of instruction, some type of action is required by the operator at the display console. This action might be picking a message on the screen by a light sensitive pen or keying in a number at the keyboard for some parameter. As soon as this is accomplished, the computer takes control once again and resumes the computation until another graphics instruction is reached. This computer graphics technique is very good when the program depends on a number of parameters which really cannot be calculated beforehand.

Another obvious use of computer graphics is to display a series of objects that interact with each other to give their relative position in two dimensions. That is, a two-dimensional plot can be established at the face of the display scope that might represent a two-dimensional layout or a three-dimensional arrangement projected onto a plane. Those of you who work in the area of external vision and use MIL-STD-850 can see that a vision plot is a two-dimensional plot of the relative locations of the windows, posts, and obstructing equipment arranged in three dimensions. Therefore, computer graphics offers a technique to generate vision plots of crew station cockpits, or for that matter, any layout or arrangement.

An earlier computer program had been written (Roberts, 1969) to compute the geometry of a window and/or its relative objects and display on a CALCOMP plotter, a vision plot in rectangular coordinates. This program proved to be a tremendous asset in the design and construction of the window system for the mockup of the FDL-5 lifting body vehicle (Roberts, 1970). It was used to size and place the windows in the most optimum position for the maximum external vision.

Early in 1970, the AFFDL acquired the use of a Control Data Corporation Digigraphics Display console for use in the generation of computer graphics. This earlier computer program, which only gave a CALCOMP paper plot, became an ideal candidate for conversion to a computer graphics program. The program was converted and immediately became a useful tool in designing crew stations and generating vision plots.

Mr. Dennis Schroll, who is also presenting a paper here at this conference, used this program to determine the external vision for his high-g cockpit. The computer program

was an ideal tool for determining the visibility at various positions for the reclining seat.

INPUT DATA

The data required to generate the plots are in three parts: design eye point, vehicle orientation, and window geometry.

Design eye point. After the coordinate system of the vehicle has been established, the design eye point must be located. This point can really be just a close approximation because the program displays the chosen position and allows it to be changed at the discretion of the operator. This option of being able to move the eye point enables the operator to look at the vision available from different positions. One application would be to look at the visibility in a fighter cockpit for the lateral head movement of the pilot to determine how much his vision can be improved. This can give the designer the change in the pilot's visual field of view over the range of head movements.

Vehicle orientation. The program generates a simulated runway which allows the vehicle to be placed at some position and angular orientation relative to it. An artificial horizon is also displayed. The position of the vehicle is established by determining the required distance to the runway, how far off the centerline it is, and the altitude. The orientation is found from the angle of pitch, roll, and yaw of the vehicle relative to an earth coordinate system.

Window geometry. The last major input is the display geometry of the windows to be plotted. First, the window must be a window whose plane can be defined by any three different points. Once the plane has been established, the window can be described by a series of up to ten straight lines and/or arc segments in that plane. The program also has the capability to display ten windows if necessary.

The concept of a window can take many forms. Of course, the obvious form is an actual window(s), which describes the external vision area. Another form might be an object or obstruction which the designer feels could create a problem within the field of view. Or, the window could be a panel or an instrument or a series of instruments which could be hidden under certain circumstances. A control stick can be generated as a window if the outline or the extremities can be defined in a plane. There are a number of different forms the window can take--it just depends on the specific application needed and what the objective is. I think in your own particular specialty, an application of a window form can be envisioned.

OUTPUT DATA

Printed and punched data. The input data of the eye point, vehicle orientation, or position, and the window geometry can be printed out in the normal manner with the regular program listing and/or it can be punched out on regular program cards. If the input data is changed in some fashion during the program, this option allows the operator to see and verify what changes he has made and give him a new set of data cards that he can use the next time the program is run.

Visibility plot. The major output data item is the visibility plot. This plot takes two forms: the graphics plot and the CALCOMP plot. The graphics plot is a visibility plot in rectangular coordinates of the windows from the design eye point. The plot is displayed in a degree to the side and degree down format which is consistent with MIL-STD-850. The display scope is approximately 20 inches in diameter and the visibility plot covers a rectangular area 18 inches wide and nine inches high. This allows for a complete field of view of ±90° in pitch and ±180° in azimuth.

The CALCOMP visibility plot is an exact duplication of the graphical plot only it is on paper for permanent record. The operator has the option to look at the graphical plot and if he wants a paper copy of it he selects the CALCOMP plot.

Perspective plot. In aiding the designer in getting a better understanding of his design, another option was written into the program called perspective plot. This plot is an actual projection of the windows or objects onto a flat plane at a chosen distance from the design eye point. The distance to the plane is determined by the operator and it scales the size of the plot. This plot gives a more realistic picture of what the pilot would see from the design eye point than does the visibility plot. As in the case with the visibility plot, the operator has the option to display it on the display scope or get a hand copy from the CALCOMP plotter.

RESULTS

I think it would be appropriate at this point to give you an example to clarify the capability of the program. Figure 1 is the outline of a front instrument panel showing a three-panel glare shield, a radar scope face, an outline of an ADI and HSI, and a display panel for an emergency light.

This figure represents a simple outline of a display panel that might be proposed for a new aircraft cockpit, which I think serves as a good example. The graphics program would be used to determine the external field of view and to see if there are any problems

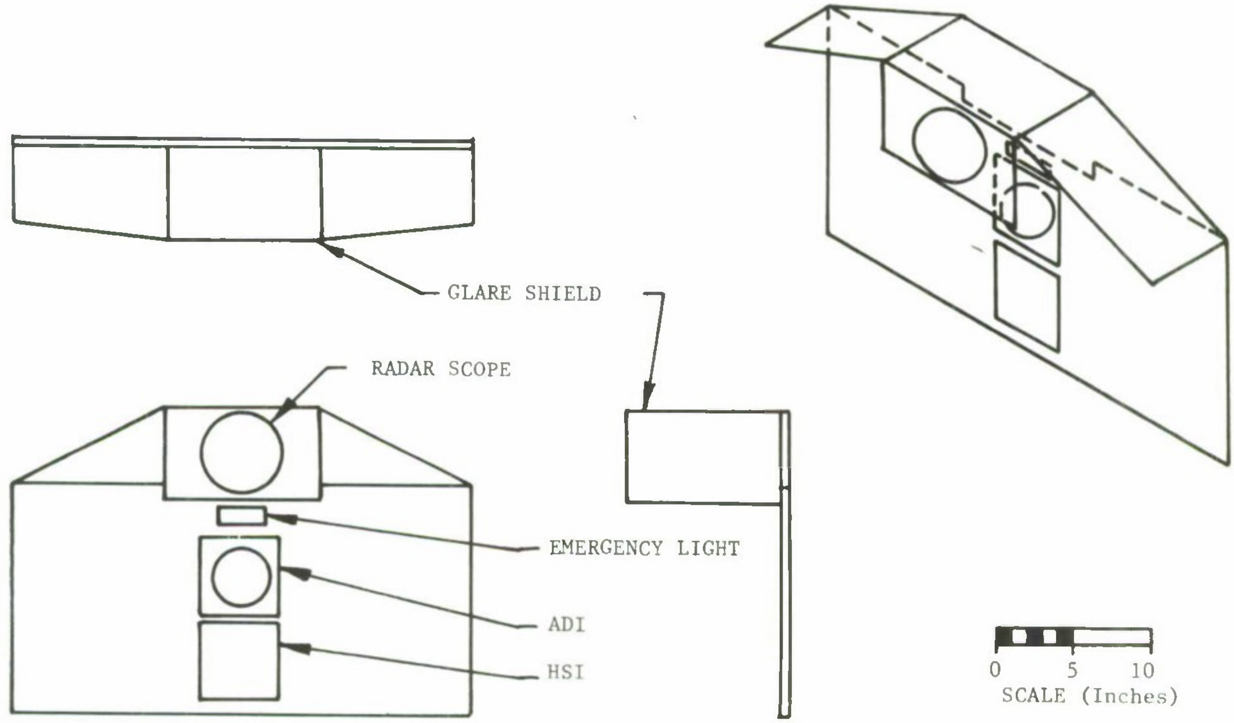

Figure 1. Outline of a front instrument panel.

associated with it. You will notice in the figure that the radar scope is protruding six inches out from the main instrument panel. Figure 2 shows the results of converting these panels and instruments into "windows" and using the computer graphics program to get a visibility plot.

This figure is an actual CALCOMP plot generated by the computer. Now, suppose the designer wants to move the eye point location up five inches to determine the maximum over-the-nose external vision. Figure 3 plots the vision angles at this new location.

It becomes very evident at this point that the emergency display light is hidden behind the radar scope. Thus, the designer knows that the panel layout is inadequate from both an internal and external vision standpoint.

Figure 4 shows the results from the perspective plot routine with the runway and horizon line added.

CONCLUSION

What I have tried to show is just a simple example of what can be done with the computer graphics program. However, I think it illustrates the concept very well. The program was kept as a very basic tool because designers tend not to use programs if they become too sophisticated and require a lot of time to apply. Therefore, we did not try to expand it to include other features or options. If you would like to learn more about the capability of the program or obtain a copy, please contact us at Wright-Patterson.

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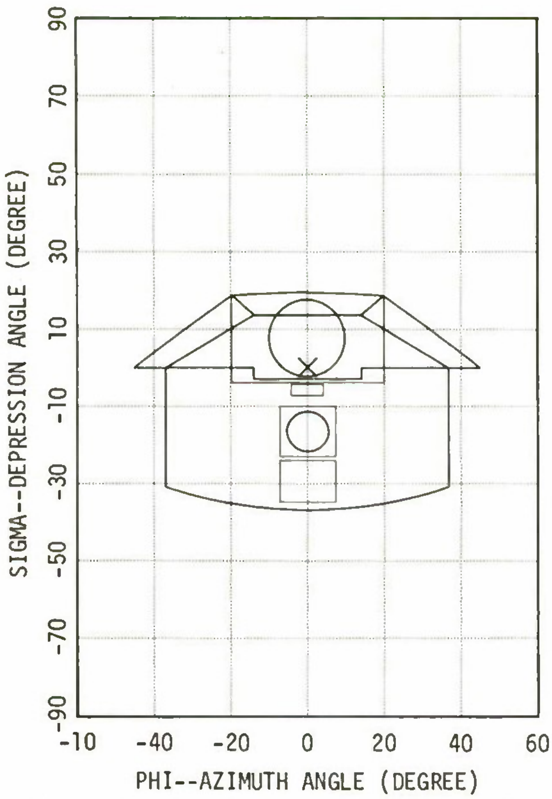

Figure 2. Results of converting panels and instruments into "windows."

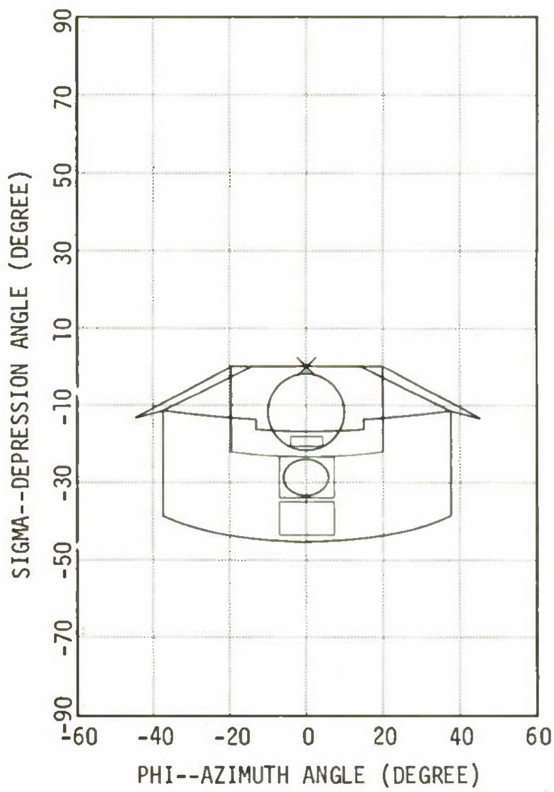

Figure 3. Plot of vision angles at new location.

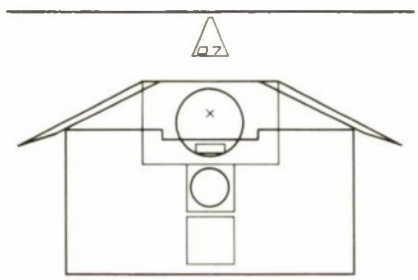

Figure 4. Results from the perspective plot routine with runway and horizon line added.

FRONTIERS IN WORKSPACE APPLICATIONS OF ANTHROPOMETRY

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Abstract: *An underlying structure of procedures and techniques applicable to all workspace designs is presented in flow-chart form. Needs for future developments in differing types of anthropometric data, improved techniques of body measurement, and application synthesis and analysis techniques are described for selected operations in the procedure.*

Illustrations of examples of current and promising approaches are presented, primarily from spacecraft and aircraft design studies. These include simplified methods of presenting design criteria for bivariate data, procedures for population synthesis (estimation from minimal data), special measurement devices and design aids, considerations of accelogravitational forces, mobility notation, key design points, and computer applications. Generality of concept in approaches is stressed, and interaction with the requirements of other disciplines is identified.

INTRODUCTION

The concept of *frontiers* suggests outer limits or boundaries of a known territory, which in this case may be called "workspace design applications of anthropometry." Figure 1 constitutes a kind of road map of the main route across the country, being a diagram of information flow through the main operations performed in this endeavor. Branching outward from each operation are paths to little-explored technological boundaries which, if explored and exploited, promise improved accuracy, speed of solution, or ease of operation. Selected examples of these paths and views toward distant horizons are discussed herein. These reports result from several years of introspection and systematic charting

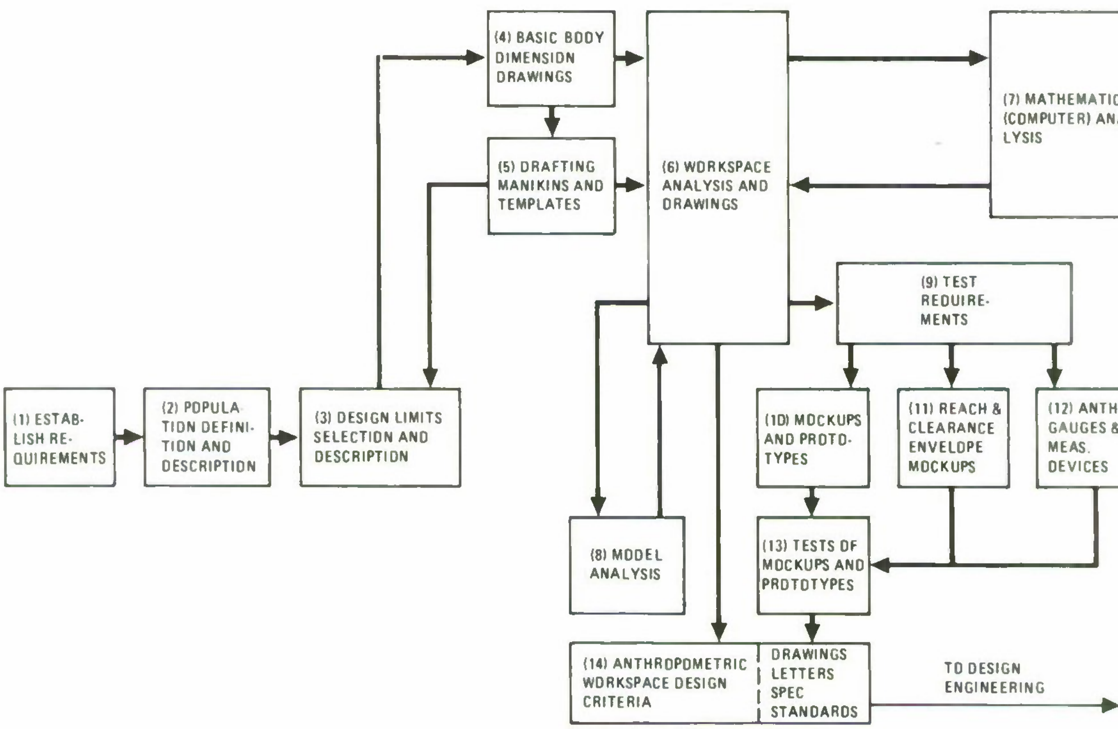

Figure 1. Anthropometric procedures for workspace design.

required to write a text book describing measurement and application techniques in engineering anthropometry.

The presentation will follow the order of the steps in the chart. A brief summary and explanation of these steps is thus warranted.

Step 1 is the systems analysis, profile of the mission, and definition of workspace and vehicle concept which leads to a description of the operator population characteristics in Step 2. Step 2 includes searching files, measuring subjects for strength and size, and/or synthesizing population dimensional and strength characteristics in statistical distribution form. In step 3, the upper and lower limits (percentiles) are selected and tabulated for design criteria. These are then formally illustrated by basic body dimensions drawings in Step 4. From such drawings one may prepare a variety of design and evaluation aids such as articulated plastic drafting manikins, templates, transparent overlays, or tracing art as part of Step 5. In Step 6, the actual design layout work begins with analyses of actual body orientations in selected neutral positions and the modification of standard body dimensions due to task efforts and accelogravitational forces. Movements and clothing effects are also incorporated in graphical layouts and results evaluated for reach and clearance, vision, etc. Mathematical model developments and computer analyses may be carried out in Step 7 to aid the workspace design effort. Three-dimensional scale models of the workspace and human occupants may be constructed as part of Step 8 to visualize complex geometrical relationships. From these steps, plans are formulated in Step 9 for full scale three-dimensional mockup development tests and verification demonstrations using special mockups (Step 10), measuring devices (Step 11), and workspace envelope representations (Step 12). These are used in the evaluations involving human subjects, dummies, etc., in Step 13 and, of course, the verified design criteria are published and disseminated to designers in Step 14.

POPULATION SYNTHESIS

The first example of a technological frontier is abstracted from Step 2 and is illustrated in another type of flow chart in Figure 2. This chart uses simplified computer logic format to show processes and decision point in synthesis of operator population anthropometric descriptions.

Beginning at the top of the chart, one gathers what data he can, compares it to what he needs, and begins to estimate what is missing. Some 20 years of experience has shown that one never has all the desired dimensional data for the desired population in workspace design. It is nearly always too little or too late. Usually these considerations are ignored, and with little error. However, historical evidence shows a growth trend in height for many Western/European populations (Figure 3). For example, U. S. Air Force flying personnel survey samples show a stature increase of 0.7 inches between 1950 and 1967 (Hertzberg, Daniels, & Churchill, 1954; USAF, 1972). It appears from the same data that their arms are getting significantly shorter. However, the measurements were not taken to test this hypothesis, so it must remain tentative at this time. These trends suggest that even further changes will take place into the 1980s when the Space Shuttle Orbiter will be operational, affecting such considerations as reach capability and seat adjustments. Thus, more information is needed about biological trends to assist in synthesizing future population descriptions from past data.

Of the many adjustments in data alluded to in the chart, the analysis of *variability patterns* such as shown in Figure 4 holds considerable promise, and needs further exploration. With such a chart, one can estimate standard deviations based only on estimated means. On another frontier, extensive publication of *correlation coefficients* enables even more accurate mathematical estimation of variances and standard deviations, when determining statistical distribution from sums or *differences* of known dimensions.

DRAFTING DESIGN AIDS

Communication of design requirements to designers through the media of graphic arts and articulated manikins, etc., is another frontier worth exploiting. Improvements in manikins, plastic overlays, and tracing forms are suggested approaches. These items are expensive, but potentially worth a great deal of saved time and improved accuracy in communication. Figure 5 illustrates an example of overlay arrangement.

ACCELOGRAVITATIONAL EFFECTS

The third example area among the frontiers is related to Step 6, and involves accelogravitational effects on anthropometric dimensions. Two aspects are considered. First is the selection of operator body orientations in the vehicle. As shown in Figure 6, the best orientation matches the human tolerance and operational capability to that of the machine, and hopefully, encloses it completely. The second aspect is that differing orientations and force magnitudes compress or release flesh, muscles, etc., and change body dimensions from those measured in classic positions. Figure 7 illustrates this with a simple example of variation of seat back angle. The

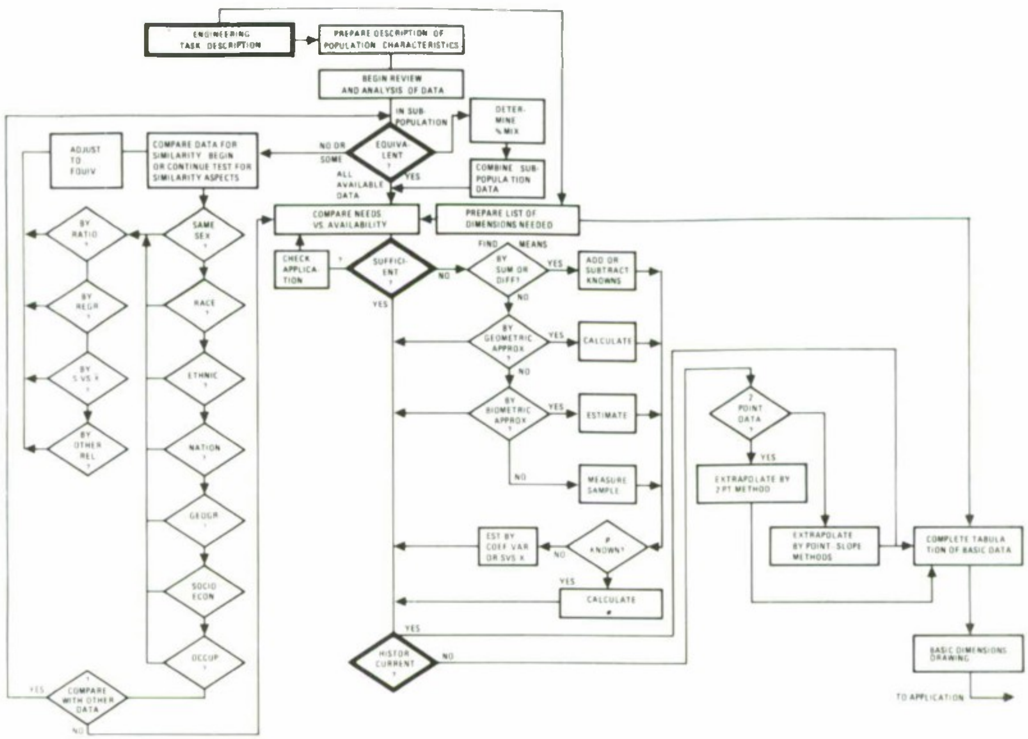

Figure 2. Anthropometric population description synthesis procedure.

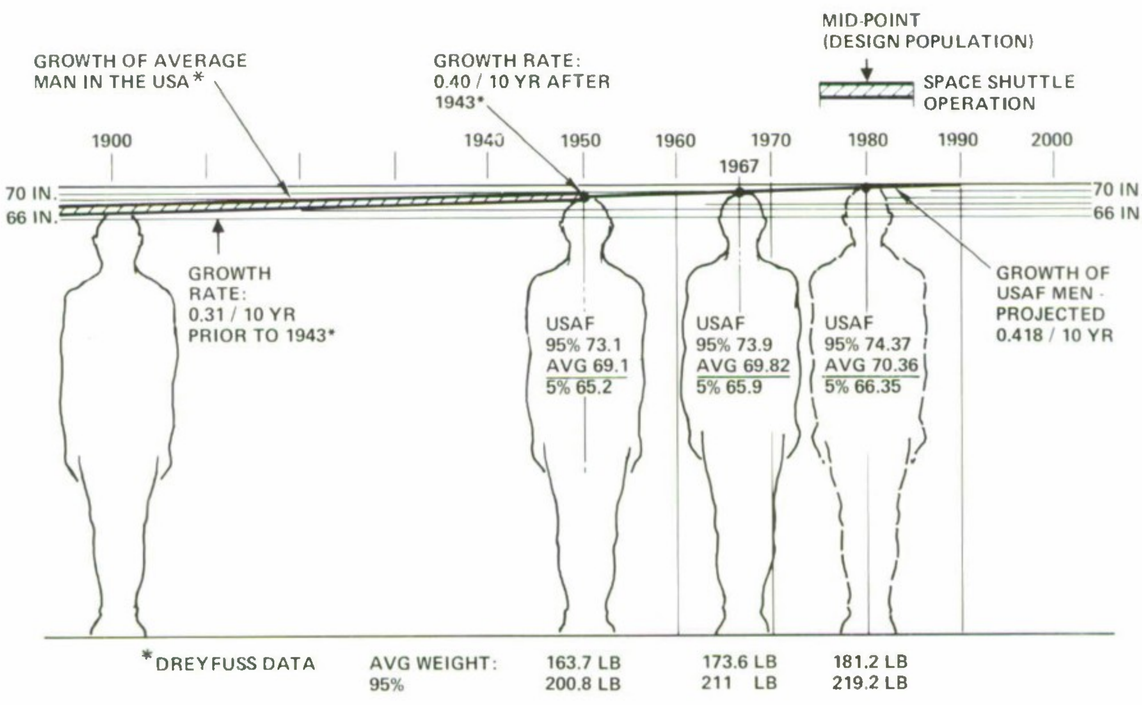

Figure 3. Anthropometric historical projection.

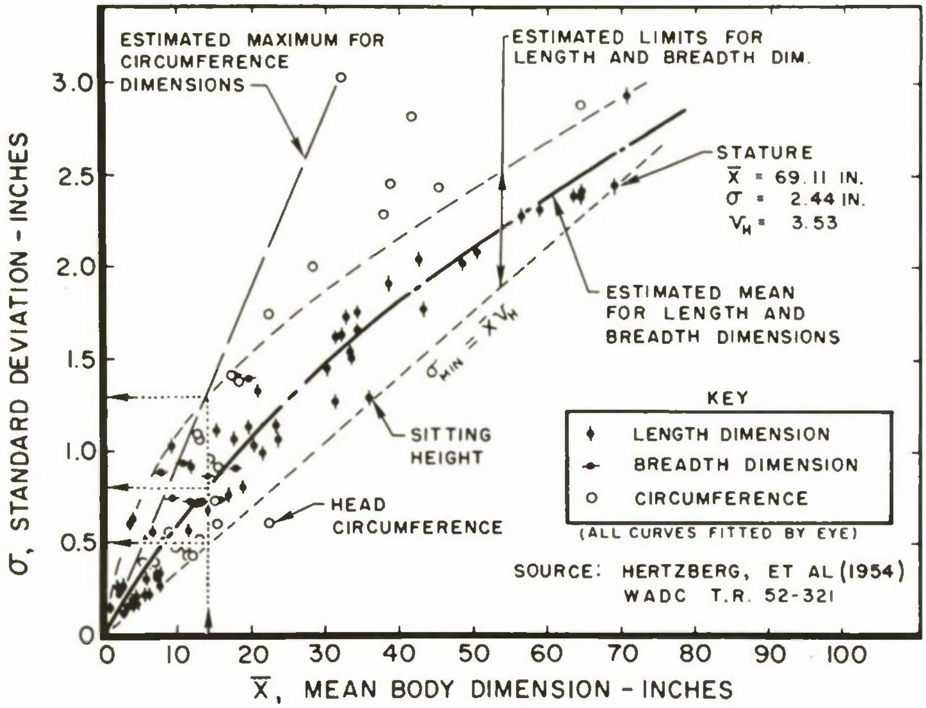

Figure 4. Example graph for estimating standard deviation as a function of mean.

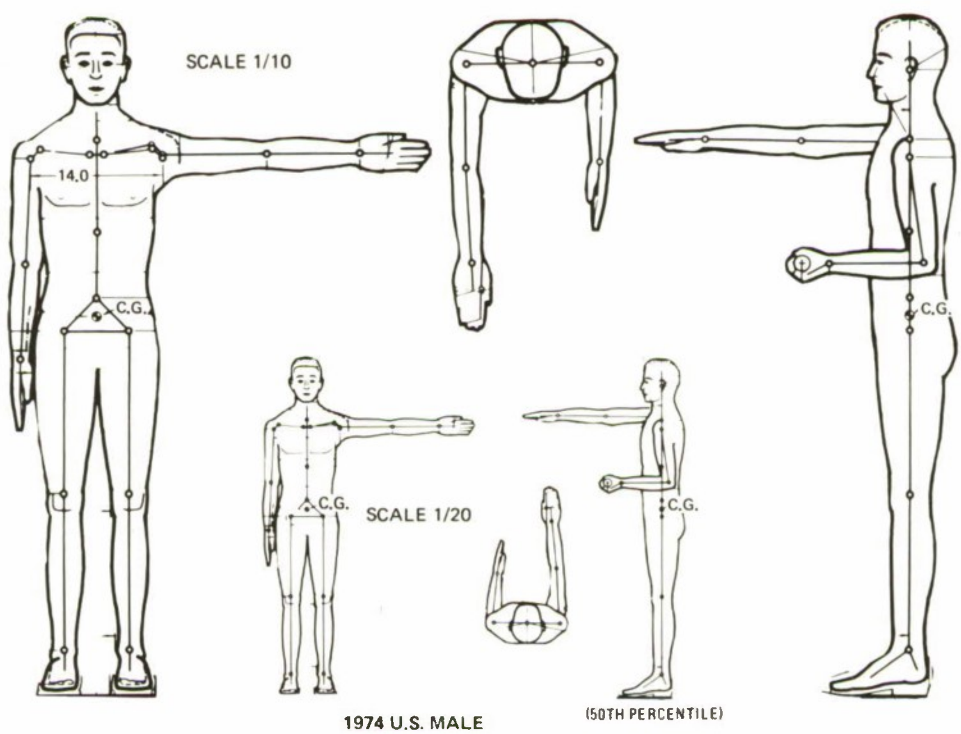

Figure 5. Example of transparent overlay for workspace evaluation.

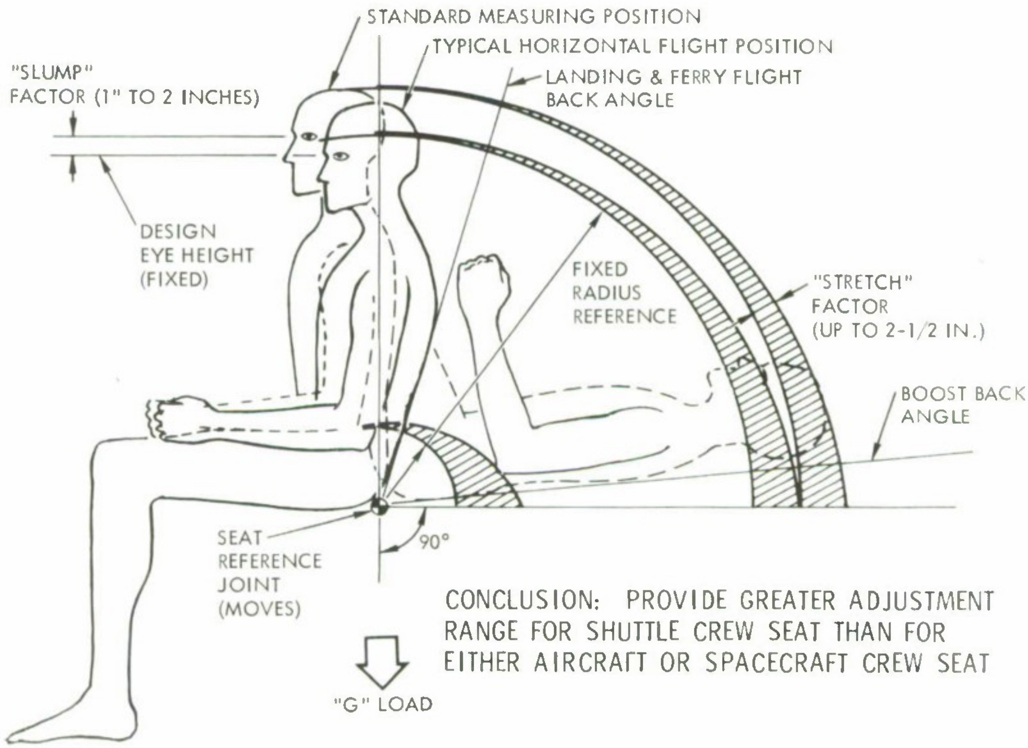

Figure 6. Body dimension changes with seat back angle.

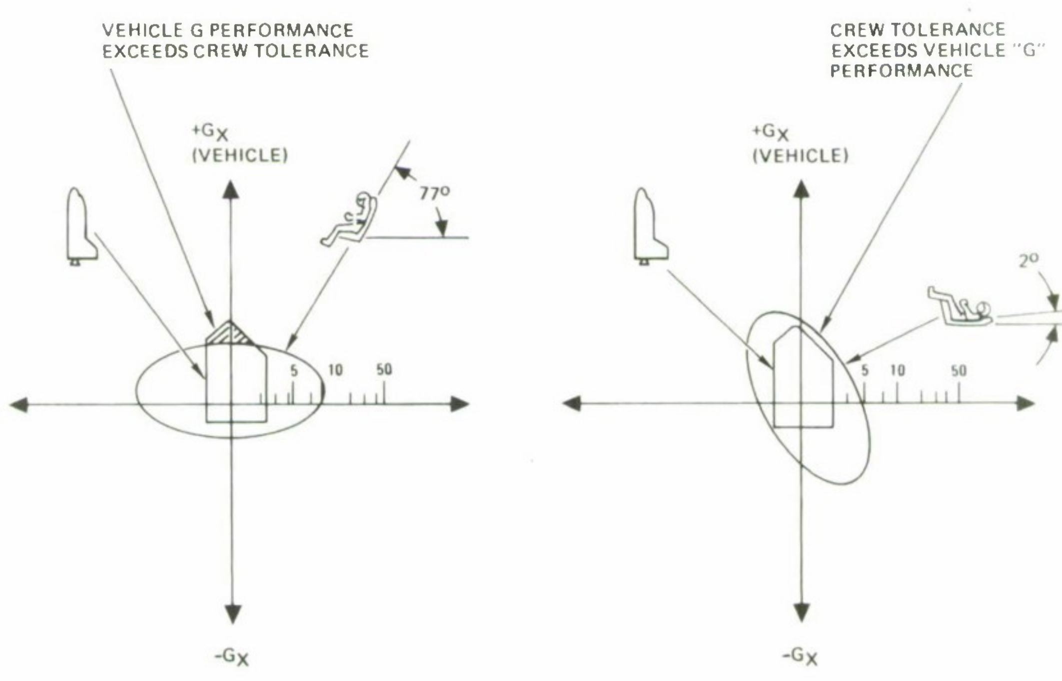

Figure 7. Example of crew body positioning by matching human G tolerance to vehicle performance G profile.

chart was derived from a few select angles. Actually, much more extensive exploration of such variabilities is needed, as well as study of human tolerances to different orientations, both in static and dynamic situations.

FIXED REFERENCE POINTS FOR WORKSPACE

A fourth consideration in workspace layout involves the selection and reporting of measurements in working situations, particularly in the concept of fixed reference points. Figure 8 illustrates such concepts.

Layout of a new station workspace is usually based on a selected fixed reference point for the operator. This is commonly a design eye point in aircraft, and a heel point in automobiles. However, most reports on measurements of reach and clearances required by the human operator refer to a fixed seat reference point and do not present data in such a way that one can transform coordinates to anywhere else. The Apollo spacecraft was actually able to use such a concept for launch and reentry duty station, because there were few critical landing or takeoff external visibility requirements. For aircraft in general, and the Space Shuttle Orbiter in particular, the visibility requirements still appear to be crucial, leading to a strong requirement for pioneer work in defining reach, both from the seat and from the design eye point, considering both fore-aft and vertical adjustments. Anything less puts an unnecessary burden on the anthropometric analyst and creates unnecessary uncertainty in the validity of design criteria.

MATHEMATICAL MODELS AND COMPUTER ANALYSIS

Step 7 opens doors to highly significant frontiers in thought patterns and procedures. Mathematical models and exacting computer routines, discussed by others in this symposium, do not permit "artistic" interpretations. Completely new emphasis on measurement procedures to obtain estimates of body link lengths, effective joint centers, and angles of motion in consistent, three-dimensional coordinate systems will be required. New, more appropriate notations and terminology for body movements which imply *rotation* instead of *translation*, as in Figure 9, can be a potential aid in this work.

A computer-controller mathematical model of the human body can enable one to save time and expenses by avoiding repeated and time-consuming mockups, preliminary tests, redesigns, and delays.

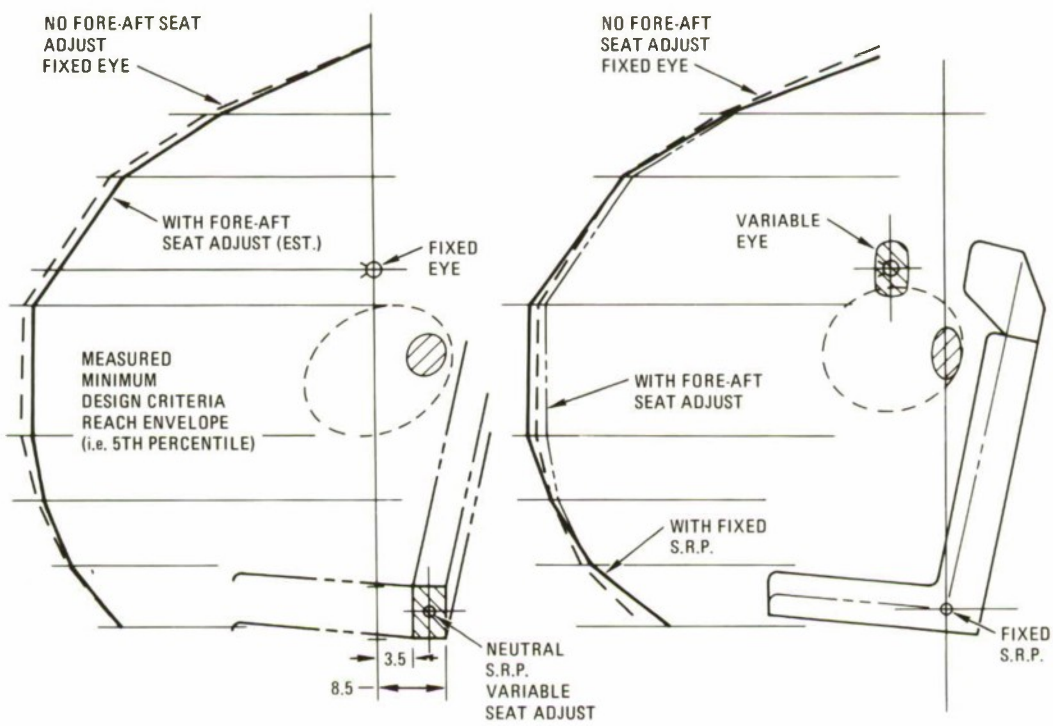

Figure 8. Comparison of fixed-eye versus fixed-seat reference point concepts for defining reach envelopes.

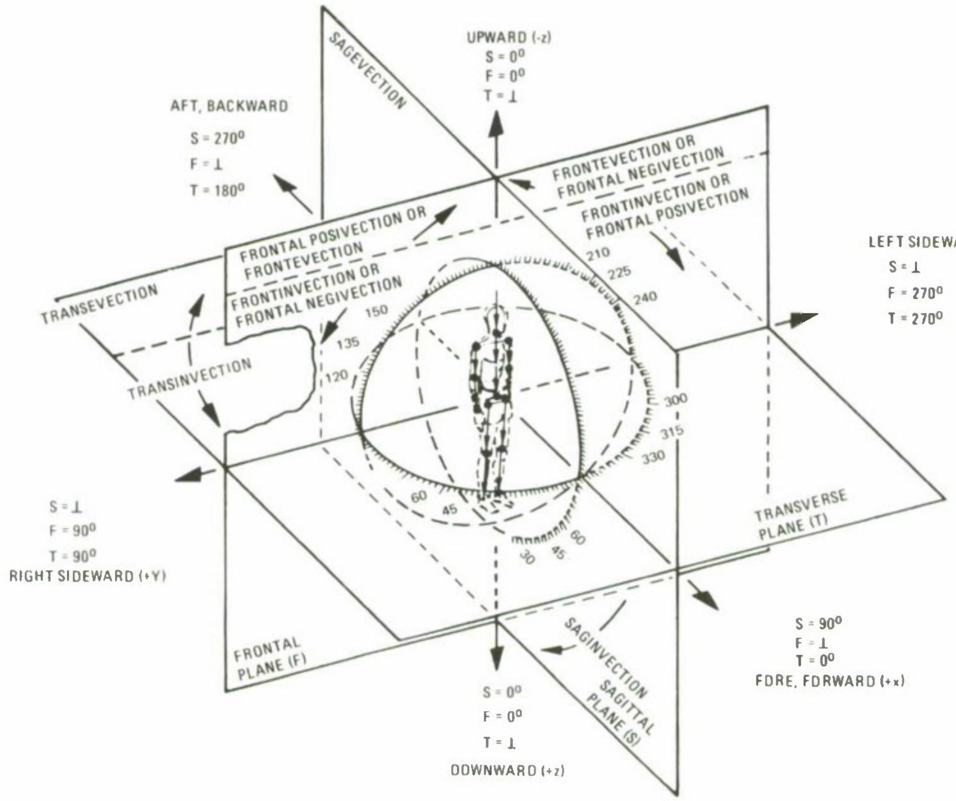

Figure 9. Proposed new mobility terminology--tri-planar angular coordinate system.

One of the advanced mathematical analogs of the human operator, oriented to interaction with the geometry of the work station, is currently being developed (Krause & Bogner, 1971; Kroemer, 1972). It is called COMBIMAN, an acronym for COMputerized BIomechanical MAN-model. This engineering tool provides:

- A reservoir of body form information: "Anthropometric Analog"
- A representation of body mechanics: "Biomechanical Analog"
- An ergonomic model of man at his work station: "Ergonomic Analog"

Standard (static) and dynamic anthropometric descriptions are handled by routine computer techniques for storing and handling of anthropometric data.

Development of a biomechanical model of the human body requires that data and findings be compatible in concept and units measured, and that links and connections (correlations at the very least) be established between them. In kinesiology and physiology, too many data and theories still stand isolated. New concepts in integration are required to meet the challenge of computerizing a biomechanical model of the human body.

Using an appropriately programmed computer, the designer is able to change the work station geometry, or the control characteristics, or the task requirements, until he arrives at a design configuration that allows optimal task performance adapted to the biomechanics of the human operator. At present, such computer-aided design is practiced only on a very small scale because the ergonomic interactions of complicated man-machine-task loops have not yet been sufficiently explored. However, an ergonomic model of a complex man-machine task can be built up, step by step, from small, simple, and succinct elements until the necessary degree of sophistication is reached. Success of the attempt to computerize anthropometric, biomechanical, and ergonomic data of man at work at his station

depends primarily on three conditions:

- Selection of clear and narrow boundary conditions within which the model must function. This applies to details as well as to the general concept.
- Ability of the model to operate initially with simple governing functions which can be replaced by better solutions as they become available.
- Selection of a suitable overall mathematical and computerization approach. A number of previous studies provide valuable experiences and guidelines.

In model design, one has to distinguish between dimensionality (two of three dimensions), configuration (full body or segments; stick model or volumetric) and the mechanics. A model may be static (without motion capabilities), kinematic (considering motion without relation to force or mass), or dynamic. If dynamic, the model design can be passive, i.e., represent the responses to externally applied energy; or it can be active, i.e., consider the internal energy capabilities (muscular strength, work, power) which can act independently from, against, or interacting with external energy.

An ergonomic analog considers the interactions between external mechanics and internal biodynamics by introducing the physics of task performance as crucial criteria (objective functions) for the adaptation of workplace geometry (equipment and environment) to the physical characteristics of the operator.

Table 1 lists, in accordance with this classification, the primary features of a number of previously described man-models and thus outlines known boundaries of this frontier. The table does not refer to external biodynamic models which serve different purposes. Such models are thoroughly described by Von Gierke (1971).

The first model, nicknamed Bulgar, was developed in Bulgaria (Popdimitrov, et al., 1969) to calculate the positions of body members if positions of the distal members and/or

TABLE 1

MODEL CHARACTERISTICS

		CONFIGURATION				MECHANICS			ERGONOMICS							
MODEL	DIMENSION	LINKS	JOINTS	VOLUME	MASS	STATIC	KINEMATIC	ACTIVELY DYNAMIC	DISPLACEMENT	STRENGTH	WORK	POWER	EQUIPMENT	ENVIRONMENT	TASK	OUTPUT
BULGAR 1967	3	14	13	-	-	x	-	-	-	-	-	-	-	-	-	LOCATION OF BODY JOINTS DEPENDING ON POSTURE
DYNASTICK 1970	3	13	12	-	x	x	-	-	-	-	-	-	-	-	-	MASS DISTRIBUTION DEPENDING ON ANTHROPOMETRIC PARAMETERS AND POSTURES
TORQUE MAN 1968	2	7	6	-	x	x	-	-	-	x	-	-	-	-	-	CHAIN OF STATIC FORCE VECTORS THROUGH JOINTS
LIFT MAN 1969	3	18	17	-	x	x	-	-	-	x	-	-	-	-	-	STATIC LIFE CAPABILITIES AT 1-g
FORCE MAN 1971	3	18	16	-	x	x	-	-	-	x	-	-	x	x	-	STATIC FORCE CAPABILITIES DEPENDING ON EQUIPMENT AND GRAVITY
MTM MAN 1970	3	8	7	-	-	x	-	-	x	x	-	-	x	-	-	BODY SEGMENT POSITIONS DEPENDING ON HAND LOCATION
SAMMIE 1969	3	18	17	x	-	x	-	-	x	-	-	-	x	-	-	BODY POSITION IN RELATION TO EQUIPMENT AND HAND LOCATION
ARM MODEL 1971	3	2	2	x	x	x	x	x	-	-	-	x	-	-	-	ARM MOTIONS DEPENDING ON POWER EXPENDITURE
BOEMAN 1971	3	23	22	x	x	x	(x)	-	x	(x)	-	-	x	x	x	FIT OF EQUIPMENT TO MAN IN RELATED BODY POSITIONS
CINCI KID 1971	3	15	14	x	x	x	x	x	x	-	-	-	-	x	x	ATTITUDE CONTROL AND MOTION IN FORCE FIELDS
COMBIMAN	3	x	x	x	x	x	x	x	x	x	x	x	x	x	x	SEE TEXT

other position and anthropometric parameters were specified. Dynastick (Wartluft, 1971) is, despite its name, a purely static stick-and-joint assembly, however, it does reflect mass properties of the human body according to the data developed by Clauser, McConville, and Young (1969). Lift, torque, and force man are static, but they do incorporate data on isometric muscle strength (Chaffin, 1969). MTM Man (Kilpatrick, 1970) incorporates in addition elementary motion times from tables used by industrial engineers. Sammie (Bonney, et al., 1969, 1971) incorporates several possible workplace configurations and utilizes elementary motion times.

Ayoub's Arm Model (1971) attempts to simulate two-link arm movements, using power for the optimization algorithm. Boeman (Boeing Company, 1970) is described by another paper in this symposium. Cinci Kid (Huston & Passerello, 1971) incorporates kinematic and kinetic aspects of the human body and also considers the environmental effects of g-fields.

The table indicates that the groundwork for a completely dynamic model has been laid through research and development, but that no such model exists so far. Hence, COMBIMAN is the next rational step to fill the gap in the computerized biomechanical man-model development.

IMPROVED WORKSPACE MEASUREMENT DEVICES

In the processes of obtaining accurate and complete anthropometric measurements in actual workspaces, new photographic devices and procedures are promising avenues of research. Simply operated, inexpensive, accurate means to place or project grids and scales at correct scale factors in the plane of measurement are needed to complement Step 11.

WORKSPACE ENVELOPES

Step 12 provides another interesting avenue for research in concepts, instruments, and materials. Automotive engineering has the H-point-machine. Who has one for aircraft seats and workspaces? Figure 10 shows a mockup three-dimensional representation of a clearance envelope for three large Apollo

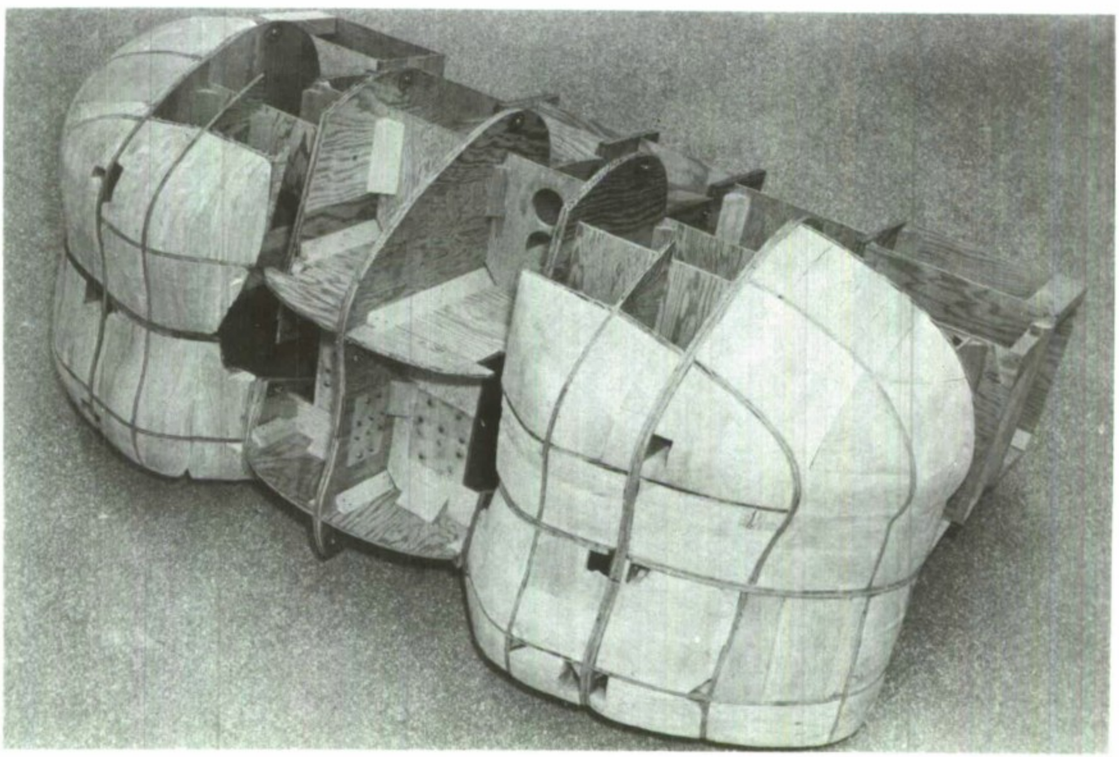

Figure 10. Mockup representation of head clearance envelope.

crewmen during land landings at a selected wind velocity from any direction. Such devices are clear demonstrations of needed volumetric space relationships, but inexpensive and rapid means to construct them are needed. Foam and paper sandwich materials are most promising to date. More difficult to construct is a useful reach envelope representation device. A hard material shell or solid form is unwieldy and not readily placed in a mockup. A better concept invovles multiple extensible arms or rods which are sufficiently separated to see through and around, and readily retracted for placement in confined spaces.

COMMUNICATION OF BIVARIATE DESIGN LIMITS

Finally, there is the problem of design criteria communication. Among the more difficult concepts to convey is that of correlated bivariate distribution limits. Figure 11 provides an approach to simplified but theoretically correct criteria description, in a form useful for design. In addition to upper and lower limits on the overall distribution of primary variables, two corners are cut off to show combinations of very low probability due to the correlation between the variables. Potential savings in adjustment ranges (as in seats, etc.) can be effected by selection of proper axes of adjustment along the major diagonal of the hexagon and perpendicular to it, or parallel to one of the other axes.

SUMMARY

In summary, the purpose of this paper has been to improve the state of the art by suggesting techniques, which may be unfamiliar to some, and by encouraging others to explore and develop these frontiers of knowledge. It is an integral part of another frontier currently being explored by the authors. That is, *education* through the medium of preparing a text book which sets forth the foregoing anthropometric procedures and frontier concepts in much greater detail and breadth of scope.

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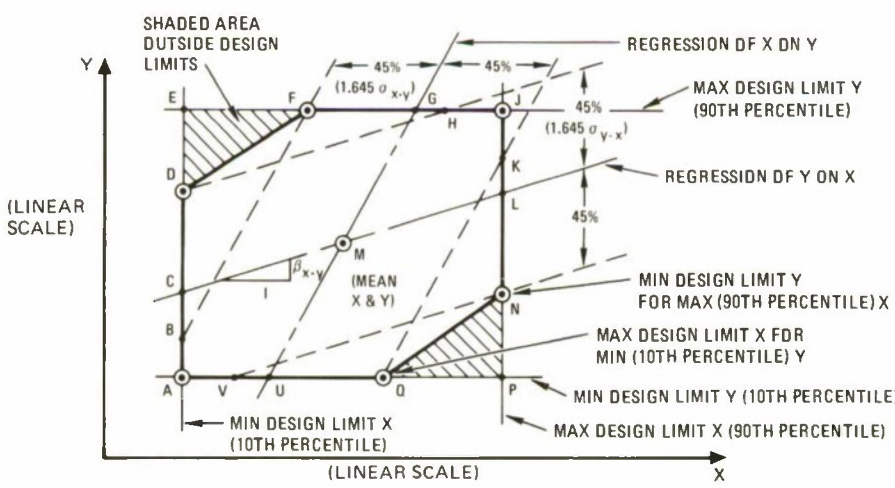

COORDINATES OF KEY POINTS (INCHES) *

VARIATES		A		D		F		J		N		D		M		P	$\beta_{y \cdot x}$	$\beta_{x \cdot y}$
X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y			
STATURE	SIT. HT	66.0	34.3	66.0	36.4	68.8	37.6	72.2	37.6	72.2	34.5	69.5	34.3	69.1	35.9	0.743	0.305	01.408
KNEE HT., SITTING	BUTTOCK-KNEE L.	22.3	20.4	22.3	21.5	23.8	23.0	25.0	23.0	25.0	21.8	23.5	20.4	23.6	21.7	0.822	0.768	0.880

* BASED ON DATA FROM HERTZBERG, DANIELS AND CHURCHILL (1954) AND UNPUBLISHED CORRELATION TABLES

Figure 11. Simplified method for describing design limits for bivariate distributions.

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RESULTS FROM A COMPUTERIZED CREW STATION GEOMETRY EVALUATION METHOD

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Abstract: *The Cockpit Geometry Evaluation (CGE) program is designed to eliminate some of the inherent limitations of present geometry evaluation techniques such as biases of the evaluator, untimely responsiveness, and high cost. A computer program system (CGECPS) has been developed and includes a dynamic mathematical man-model (BOEMAN) capable of simulating the movement paths of any-sized seated operator. Consequently, reach infeasibilities, visual interferences, physical interferences, and performance indicators can be ascertained for any crew station early in the design process. In addition, the system includes computer graphic displays of the geometry being evaluated and the man-model movements, as well as the option to subject the design to compliance checks against geometry oriented Military Standards and Specifications.*

A "levels of evaluation" concept has also been developed and the CGECPS has been subjected to initial validation on the A-7E crew station. The results were highly encouraging. The extension of the CGECPS to other crew system problems has also been investigated. While many areas are promising, the evidence would indicate that several components of the CGECPS are directly applicable to computer aided design with interactive graphics--an area that the Crew Systems Technology has been remiss in developing.

INTRODUCTION

The Boeing Company and the Joint Army-Navy Aircraft Instrumentation Research (JANAIR) Program Working Group initiated a program in 1968 to improve the methods for evaluating the geometry of cockpits and other seated crew stations. This program entitled Cockpit Geometry Evaluation (CGE), is designed to utilize the speed and flexibility of scientific computers to evaluate the physical compatibility of a seated crew member of any size with any crew station beginning with the design concept. Present geometry evaluation techniques such as drawing reviews, mathematical models, mockup flight simulators, and prototype flight tests have all been refined over the years and produce useful data. However, they all have one or more of the following inherent limitations: biases of the evaluator, lack of standardization, and the inability to take into account the full variability in flight crew anthropometry.

The CGE program was designed to eliminate these limitations. However, it was recognized that the task would be formidable because of the very nature of the crew system technology. Whereas improvements to other aircraft subsystem designs depend only on the laws and breakthroughs of physical science, improvements to the cockpit subsystem and its evaluation depend on the proper integration and applications of the laws and theories of physical science and the behavioral sciences. That is, engineers, physiologists, psychologists, anthropologists, etc., must pool their knowledge to provide missing data. A need for more quantitative laws in the behavioral sciences complicates the problem.

One of the principles kept in mind during the CGE effort to date is that development of total evaluation method of crew stations should be oriented toward the concept of an overall single-figure-of-merit rating. The cockpit factors that should constitute the figure of merit must be determined. Moreover, the best methods for determining each factor and how they should be combined to form the figure of merit must be determined. Some of these factors, a flow diagram suggesting a gross relationship between them, and the relationship of the CGE program to the overall evaluation technique are shown in Figure 1.

Cockpit geometry, enclosed by the dotted lines, is only one factor of the total crew station evaluation problem. However, its selection for an extensive developmental effort is a logical first step. Such a technique will aid in providing the design engineer with improved tools for design optimization. The physical geometry was selected because it is primarily a mathematical consideration. Hence, it is more adaptable to

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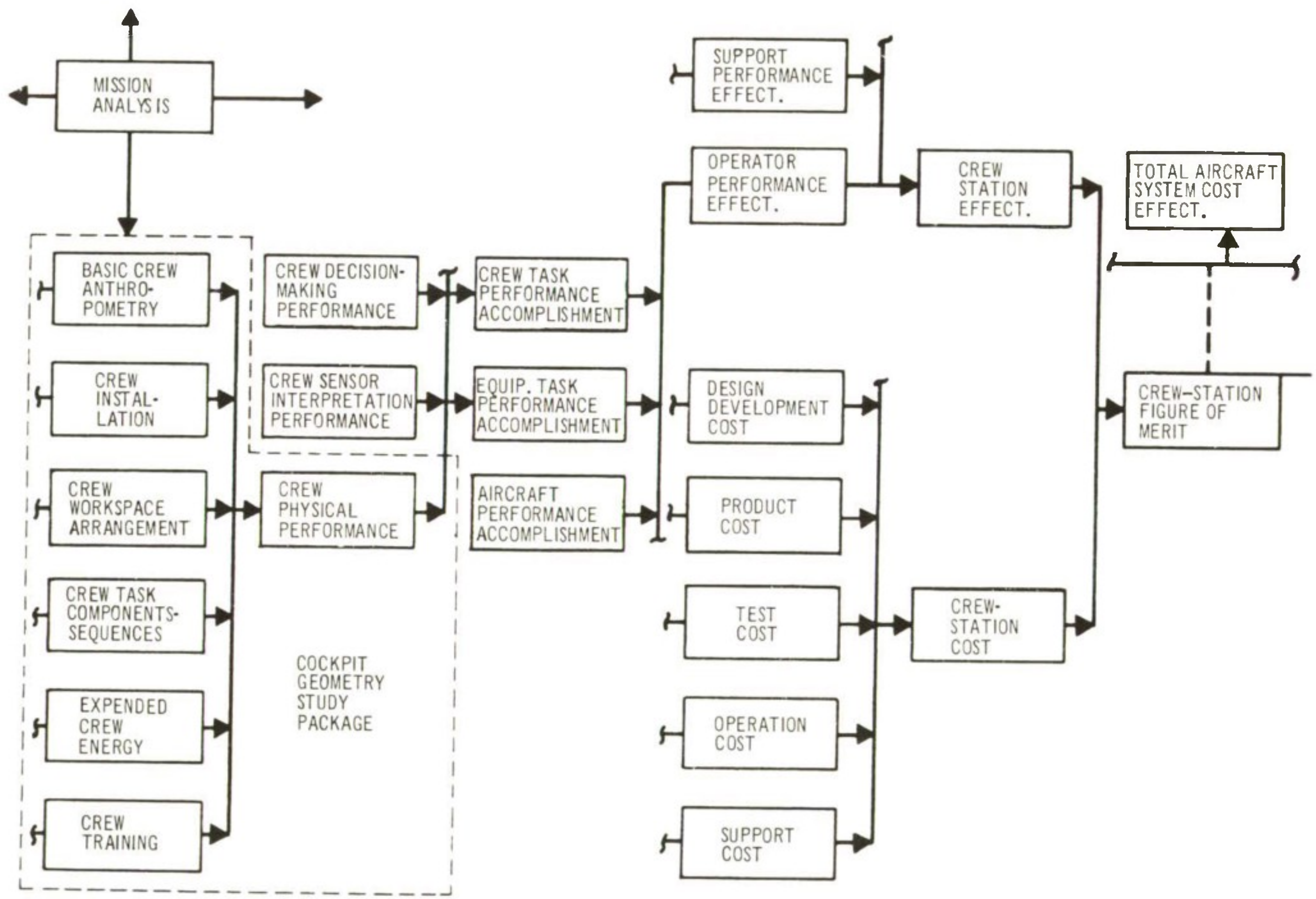

Figure 1. Abbreviated crew station evaluation flow diagram.

computer methods than mental processes associated with decision-making capabilities are.

At the outset of the CGE program, it was established that the method to evaluate cockpit geometry through crew physical performance should:

- Be applicable in all stages of crew station development from concept to actual operations,
- Permit the evaluator to consider dynamic motion, variation in operator/size, simple and complex actions, and physical restraints,
- Provide a common reference to compare the physical parameters of the operator and the crew station layout,
- Permit specific items of interference with crew performance to be identified and indicate areas where improvement will be most beneficial,
- Produce repeatable results, regardless of the investigator,
- Produce results in a form that is applicable for either program management or design development decision,
- Permit evaluation to be accurately performed with a minimum of time and expense, and
- Establish validity by test.

The CGE program was originally planned as a six-phase development (see Figure 2), each of 12 months' duration. The accuracy, flexibility, and thoroughness of the tool would be improved with each phase. Each year's effort, however, was designed to provide an end product of immediate use to military and civilian designers. A long-term development by a relatively small but highly specialized team appeared to be the most feasible approach to the problem, as opposed to a faster development using a large team. The results to date have supported this approach even though some changes in the original plan have been made. Figure 3 illustrates how the six-phase plan was combined into an overall design.

RESULTS TO DATE

GENERAL

Three phases of the CGE program have been completed, and the following is a synopsis of the major program achievements to date.

We have developed a dynamic mathematical man-model with an internal link structure, quite similar to the human body segments as shown in Figure 4. The dynamic movement capability of the model is provided by using Euler angles to configure the link system and then minimizing a non-linear objective function with both non-linear and equality constraints to provide movement.

- Development of mathematical routines to detect and correct where possible for visual interference and to detect, determine the extent of, and possibly avoid physical interference,
- Development of mathematical routines to describe the geometry of a crew station,
- Development of computer graphic routines to display both the man-model and the crew station geometry (Figure 5),
- Development of a single camera multiple mirror technique for determining human motion paths (Figure 6),
- Statistical validation of the man-model joint movement paths when compared with the human motion data,
- Development of computer routines to check for crew station compliance with selected military standards and military specifications which are geometry oriented (e.g., MIL STD 1333),
- Development of a "levels of evaluation" technique to increase the efficiency and the economy of the evaluation process, and
- Evaluation and preliminary validation of the CGE technique by applying it to the A-7E cockpit.

The last three program achievements are of the greatest interest to the group assembled here and hence further discussions will be limited to them. Specifics on the other aspects of the CGE program are available from the author upon request.

MILITARY STANDARDS AND SPECIFICATION COMPLIANCE TESTING

The military standards and military specifications compliance testing program was developed because it became clear during the CGE development that the geometry oriented standards and specifications contained valid requirements that, when adhered to in the crew station design process, would result in generally acceptable crew stations. The problem is that the requirements are numerous,

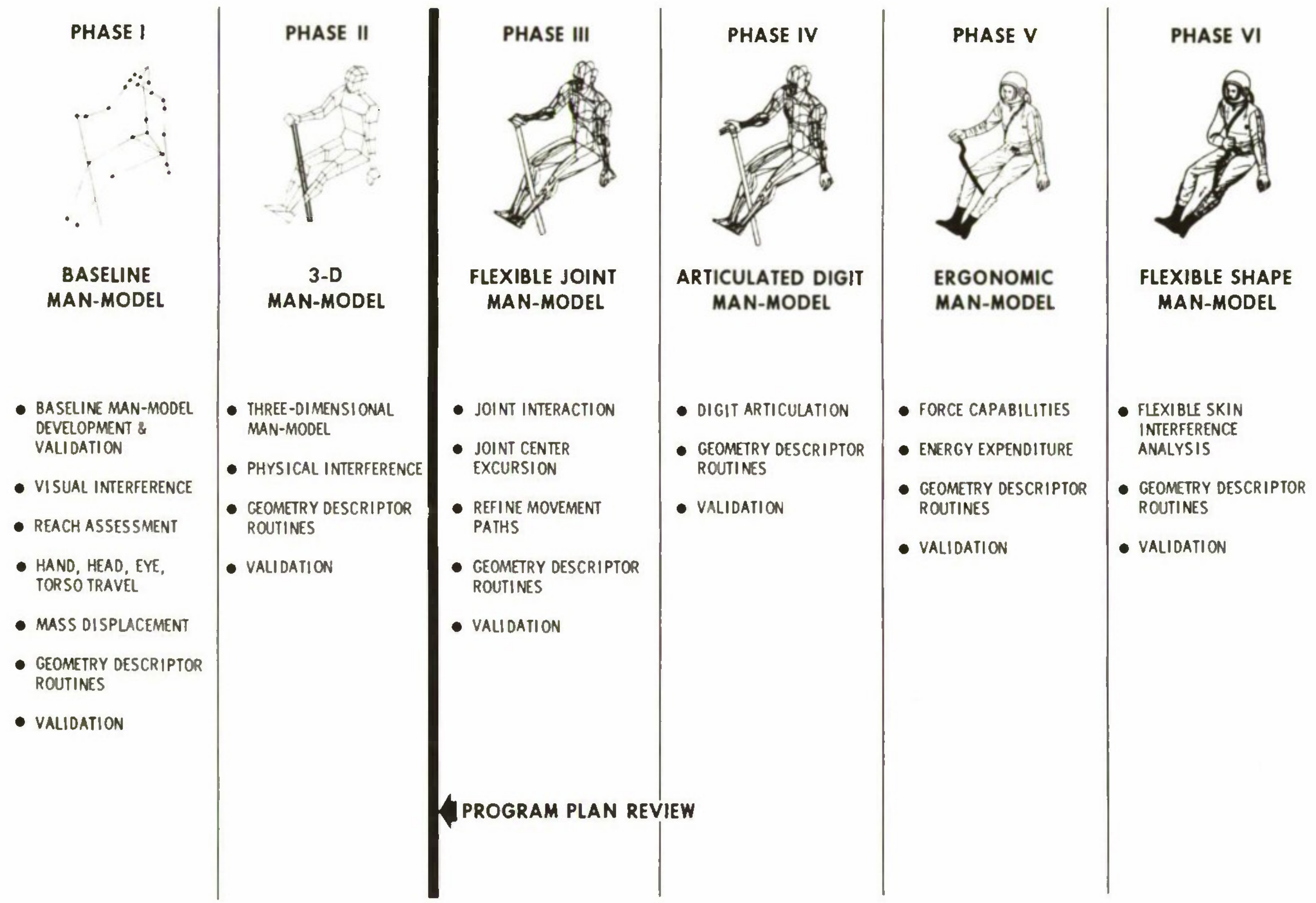

Figure 2. Original research plan summary.

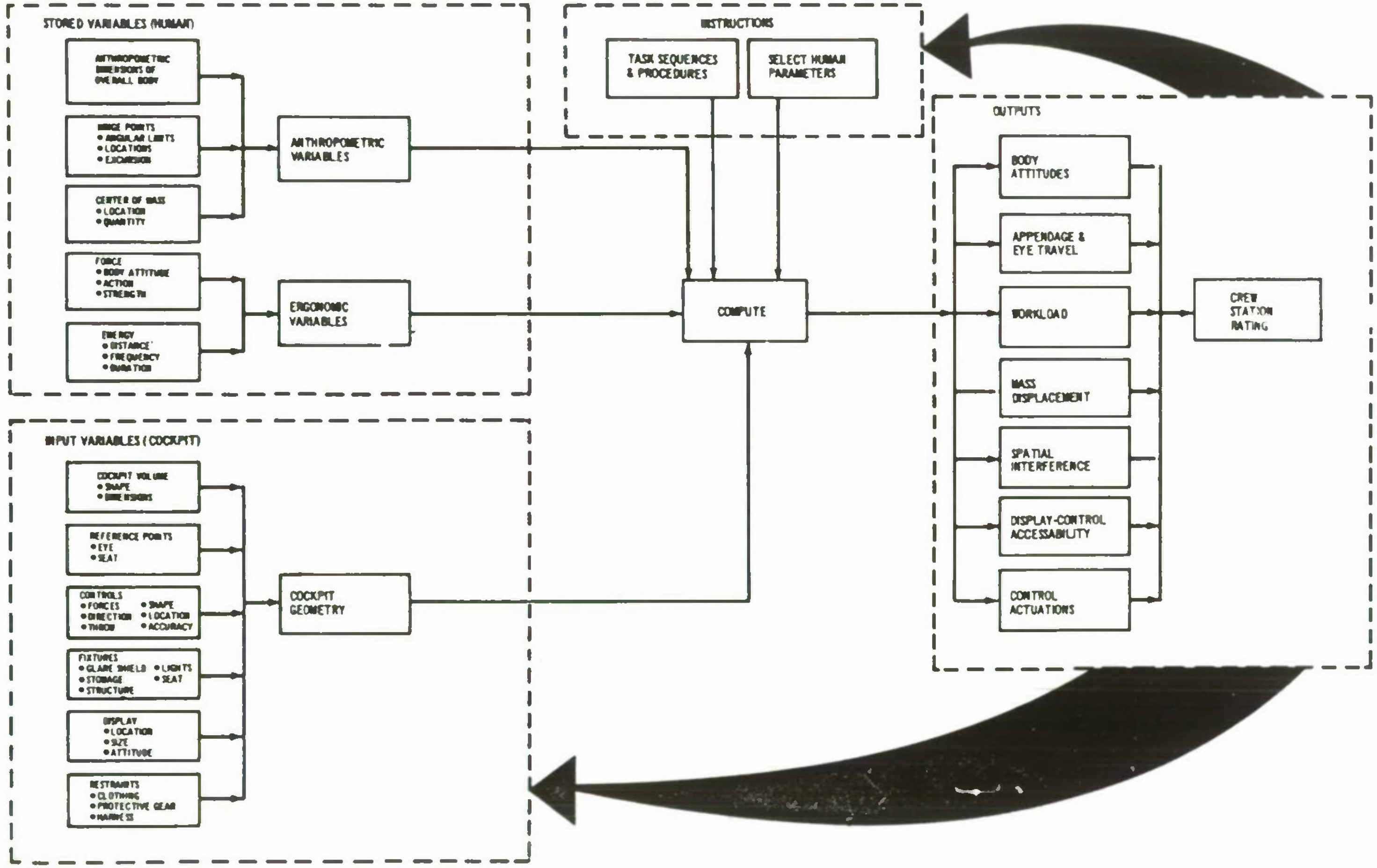

Figure 3. Cockpit geometry evaluation program design.

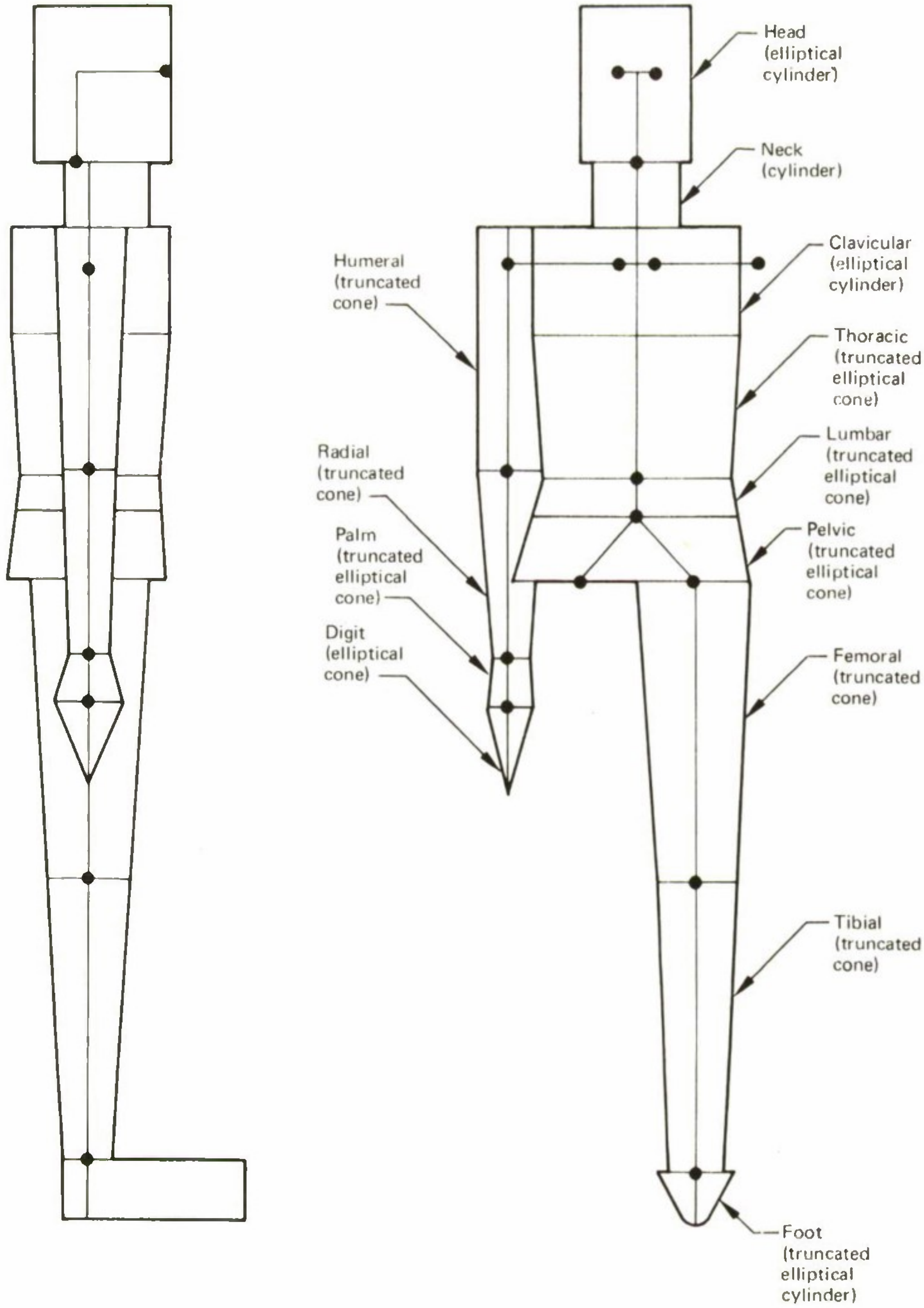

Figure 4. BOEMAN-II

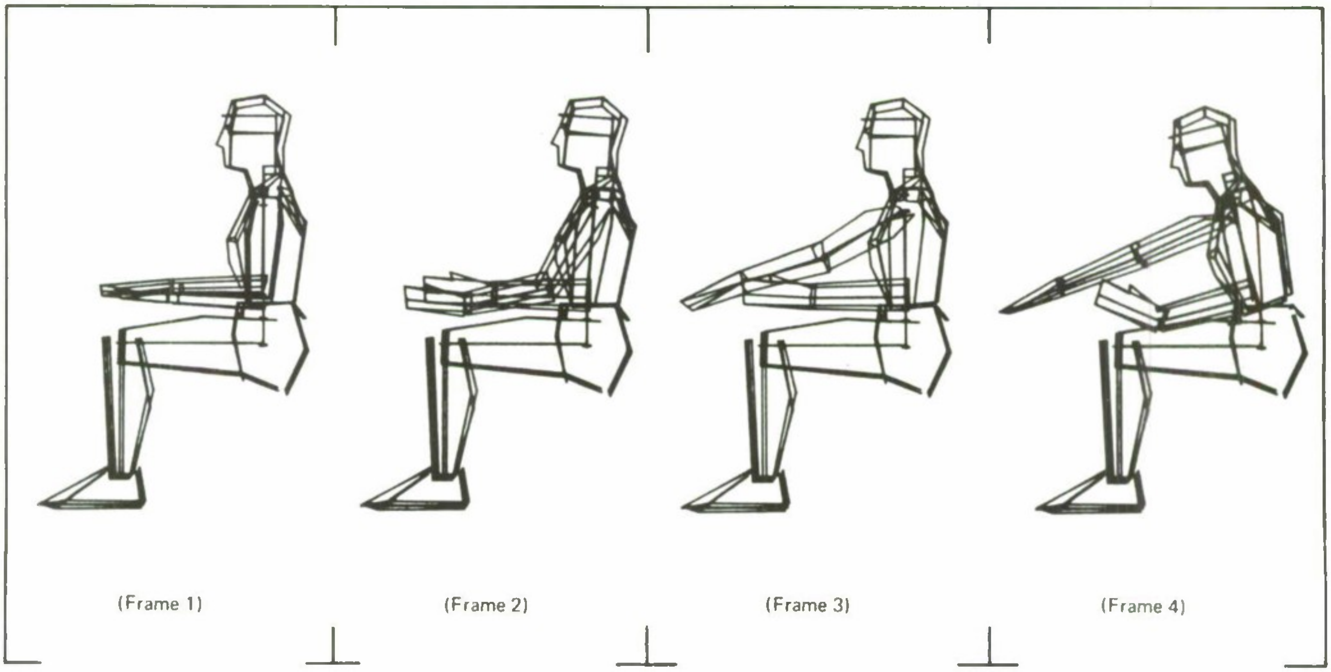

Figure 5. Computer graphic plot of BOEMAN performing a task of the basic validation sequence.

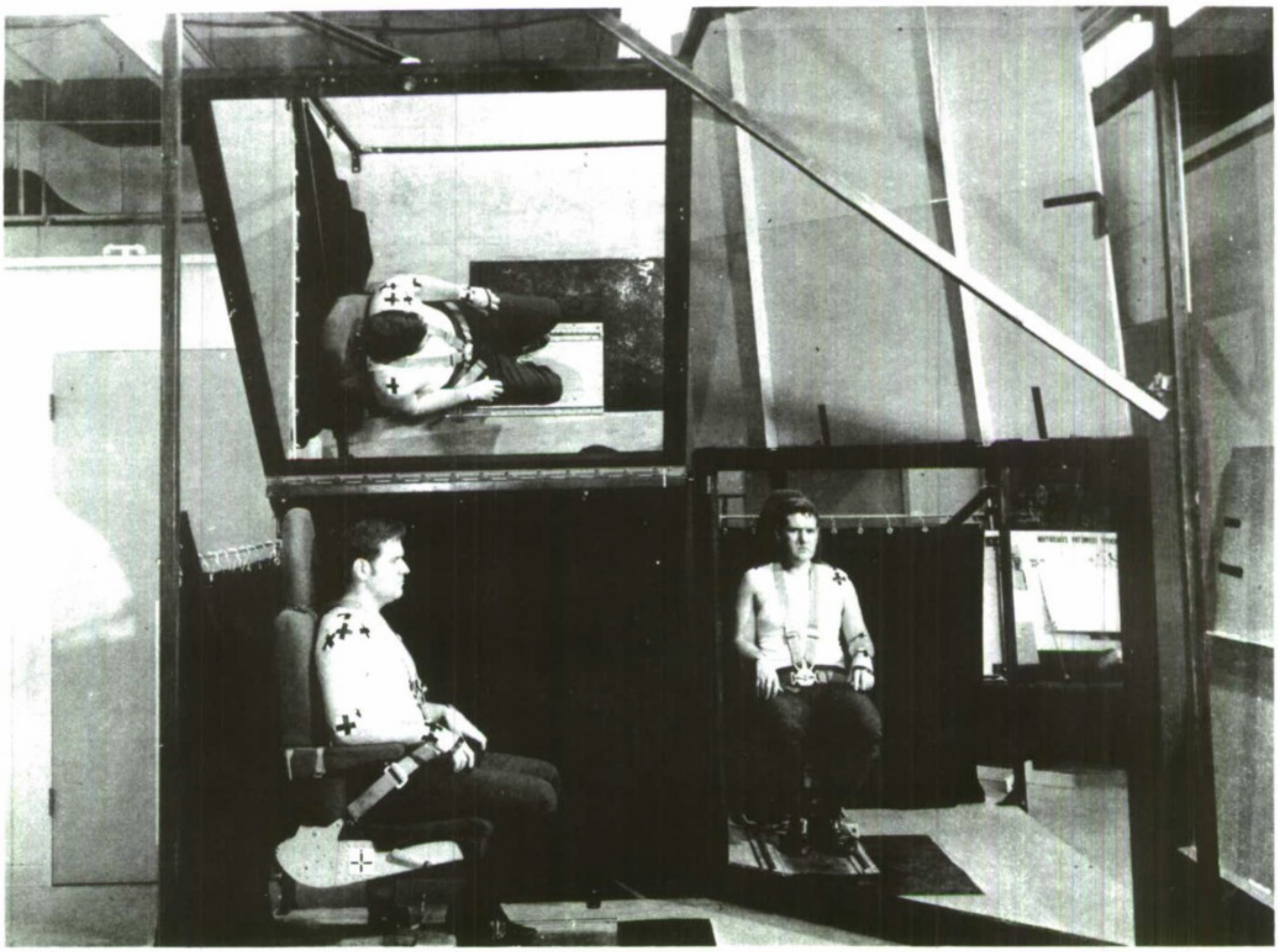

Figure 6. Multiple mirror technique for filming human movement.

sometimes complex, and unfortunately sometimes in conflict or detrimental to the design.

Because requirements are so numerous and sometimes complex, compliance checking is done on only a limited number by the designer in industry. Those checked are the ones he considers critical (e.g., seat reference point to eye reference point, stick reference point location and travel). The military evaluator also only has time during proposal evaluation to test for compliance on the requirements he considers critical, which for the most part are the same ones as the designer selects. Obviously, if it were significantly easier to check for compliance, both designer and evaluator would benefit.

Therefore, geometry standards and specifications were analyzed to determine what compliance checks could be computerized. Specifically MS-333573, MS-33574, MS-33575, MS-33576, MIL-STD-203E, MIL-STD-250C, MIL-STD-1333A, and MIL-STD-850B were analyzed.

Examples of requirements that were deemed testable for this study were arm reach envelope definitions, head to canopy clearances, arm and leg to panel interference, visual interference, viewing distance, control placement, and distances from cockpit reference points and planes.

After identifying the computer testable requirements, possible testing methods were examined. Two types of tests were developed. One test uses vector geometry to calculate distance and direction. The second type uses the man-model (BOEMAN) of the CGE program to determine physical and visual interference, sufficiency of clearance, feasibility of a fully restrained crew member being able to reach certain controls, etc.

The compliance testing program has gone through initial checkout on the A-7E cockpit, and the results are encouraging. For example in checking against MIL-STD-1333A, the program defines which controls are within the three reach zones, and the compliance/noncompliance of the stick reference point bounds.

While reviewing the military standards and military specifications for computerized compliance checking, it was anticipated that certain specific discrepancies and possible improvements would be discovered. One of the major discrepancies uncovered was the conflict between the reach zone requirements of MIL-STD-1333A and the ejection clearance plane of MS 33573 and MIL-STD-1333A as shown in Figure 7. As is evident, any control on the front panels will be beyond the Zone 2 reach envelope.

"LEVELS OF EVALUATION" CONCEPT

An analysis of the Cockpit Geometry Evaluation Computer Program System (CGECPS) was undertaken during Phase III to provide an assessment of its status, deficiencies, growth potential, and applicability. The analysis was considered under four categories: 1) applications, 2) scope reductions, 3) additions, and 4) improvements--a) interference, b) computer techniques, and c) man-model movement.

The modular nature of the CGECPS, although designed and integrated into an overall system, allows for individual capabilities that could focus on and resolve other crew station or crew station related problems (e.g., maintainability). Extended applications then, were logical follow-ons to the original concept since many man-machine interfaces have evaluation requirements similar to those of the seated crew station operator. Although military crew station applications predominated, consideration was also given to some non-military applications. Inherent in the area of applications is system analysis for scope reductions and for additions. The reductions would indicate what parts of the CGECPS could be used by themselves or in combinations (as a subsystem) for a given application. Additions would include the portions of a module that must be augmented for a given application. In addition, improvements to the current CGECPS were studied for savings in computer time, storage, and greater capability. Specifically, the applicability of the CGECPS and/or its components to such things as Computer Aided Design (CAD), Air Traffic Control (ATC) stations, and electronic microchip design, were examined. Table 1 summarizes the applicability of the findings.

In analyzing the area of scope reduction, some new concepts were generated, namely a "levels of evaluation" concept, a Reach Basket Model (RBM), and a Reach Envelope Evaluation Method (REEM).

The "levels of evaluation" concept is an attempt to satisfy various evaluation criteria. Namely, often a total CGECPS type of evaluation is not required; rather specific areas of evaluation are desired such as reach and vision checks. Therefore, if a series of evaluation tests could be developed, the concept of computerized evaluation would be even more responsive and economical. Figure 8 illustrates this "levels of evaluation" concept.

One of the elements of the "levels of evaluation" concept is a Reach Basket Model (RBM). As envisioned, the major reasons for developing a Reach Basket Model (RBM) were that: such a model would allow a quick check of reach compatibility of any crew station under a variety of conditions (e.g., physical

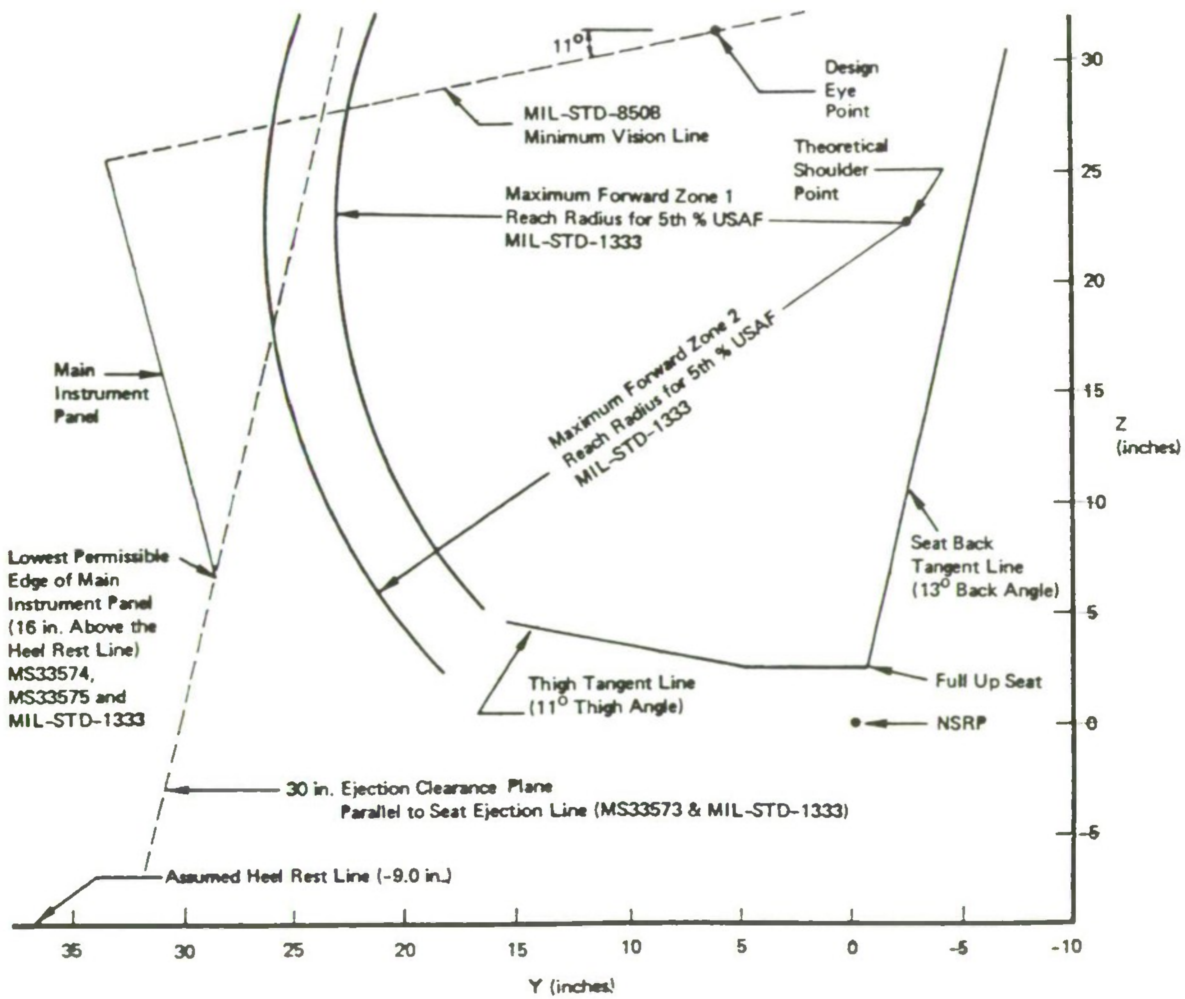

Figure 7. Conflicts between reach and ejection clearance requirements.

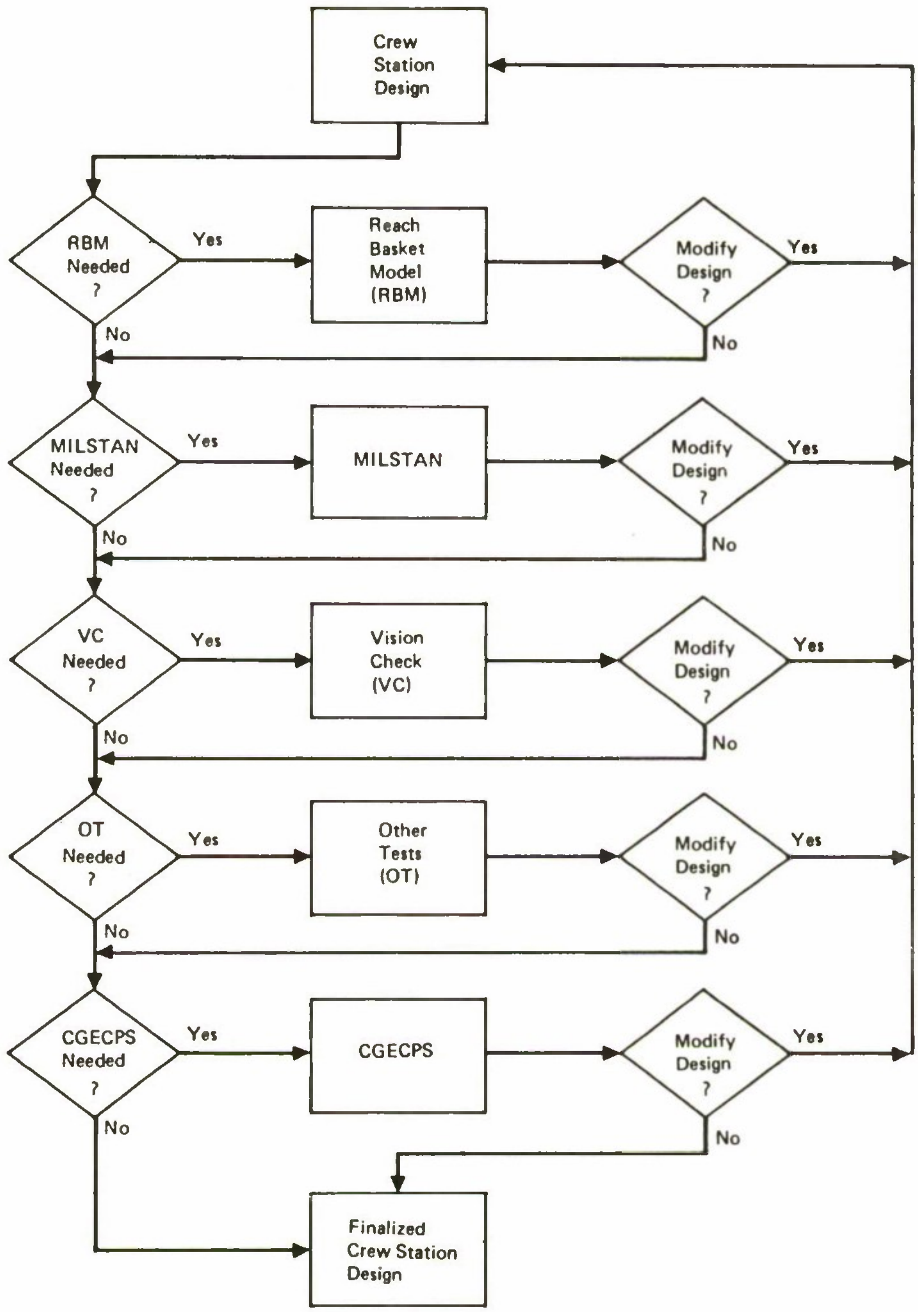

Figure 8. Levels of evaluation concept for optimizing crewstation geometry.

TABLE 1

ANALYSIS OF CGECPS COMPONENTS VERSUS POSSIBLE APPLICATIONS

CGECPS COMPONENTS	CAD	ATC	SPACE STATIONS	PACKAGE ENGRG	ASSIGN-ABILITY	MICRO-CHIPS, ETC.	AUTOS	COMPUTER TERMINALS	TANKS, SUBS, SHIPS	RAPID TRANSIT, ETC.
GEOMETRICAL DATA	Y	Y	Y	Y	Y	?	Y	Y	Y	Y
DATA CHECK	Y	Y	Y	Y	Y	?	Y	Y	Y	Y
TASK DATA	?	Y	Y	X	?	X	?	Y	Y	?
ANTHROPOMETRIC DATA	?	Y	Y	X	Y	X	Y	Y	Y	Y
MILSTAN	Y	?	X	X	X	X	X	X	Y	?
VECTOR CALCULATIONS	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
PI METHODOLOGY	Y	?	Y	Y	Y	Y	Y	?	Y	?
PIA METHODOLOGY	Y	?	Y	Y	X	Y	Y	?	Y	?
VI METHODOLOGY	Y	Y	Y	X	Y	X	Y	Y	Y	Y
VIA METHODOLOGY	Y	Y	Y	X	X	X	Y	?	Y	?
BGE	?	?	Y	X	?/Y	X	Y	?	Y	?
LINK SYSTEM ONLY	?	?	X	?	?/Y	X	X	?	X	?
SUMMATION ROUTINES	?	Y	Y	X	X	Y	Y	Y	Y	Y
OPTIMIZATION TECHNIQUES ONLY	?	?	X	Y	X	Y	X	Y	X	X
STATISTICAL COMPARISON	X	X	Y	X	X	X	Y	?	Y	?
VALIDATION	X	X	Y	X	X	X	Y	?	Y	?
PLOTTING	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Y = COMPONENT USEFUL TO THE GIVEN APPLICATION
X = COMPONENT NOT USEFUL TO THE GIVEN APPLICATION
? = COMPONENT USEFULNESS TO THE GIVEN APPLICATION CANNOT BE FULLY DETERMINED AT THIS TIME

restraints, cockpit controls, hand orientations, and acceleration forces) for any sized crewman. The maximum reach points synthesized by the RBM would then be connected by some means to form enclosed reach envelopes. The resulting reach envelopes could be stored on computer tape for reuse in checking any crew station design. Moreover, if the basic mathematics of the CGE man-model could be used for the RBM, the development time could be significantly reduced. As it turns out, the mathematical model could serve as an excellent baseline, hence the RBM was developed.

The next step was to devise a way of determining the entire reach envelope for a given size operator. Basically, the technique proposed and currently under development is to:

1. Have the RBM determine a sufficient number of points to define the reach envelope,

2. Then use a Geometric Objects Manipulation Program (GOMP) to fit surfaces between the points,

3. Store this reach basket on computer tape for permanent storage and reuse, and

4. Finally, overlay the reach basket data on the crew station design to determine which controls lie within the reach basket.

Obviously, by altering the anthropometric data of the RBM (i.e., link lengths, joint angular limits) a series of reach baskets can be created and all tested against the crew station design if desired. Figure 9 illustrates the REEM development.

EVALUATION OF THE A-7E

The first two phases of the CGE program were primarily research and development phases. However, the excellent man-model validation results of Phase II indicated that the CGE developments had progressed to a point where validation of the entire CGECPS should

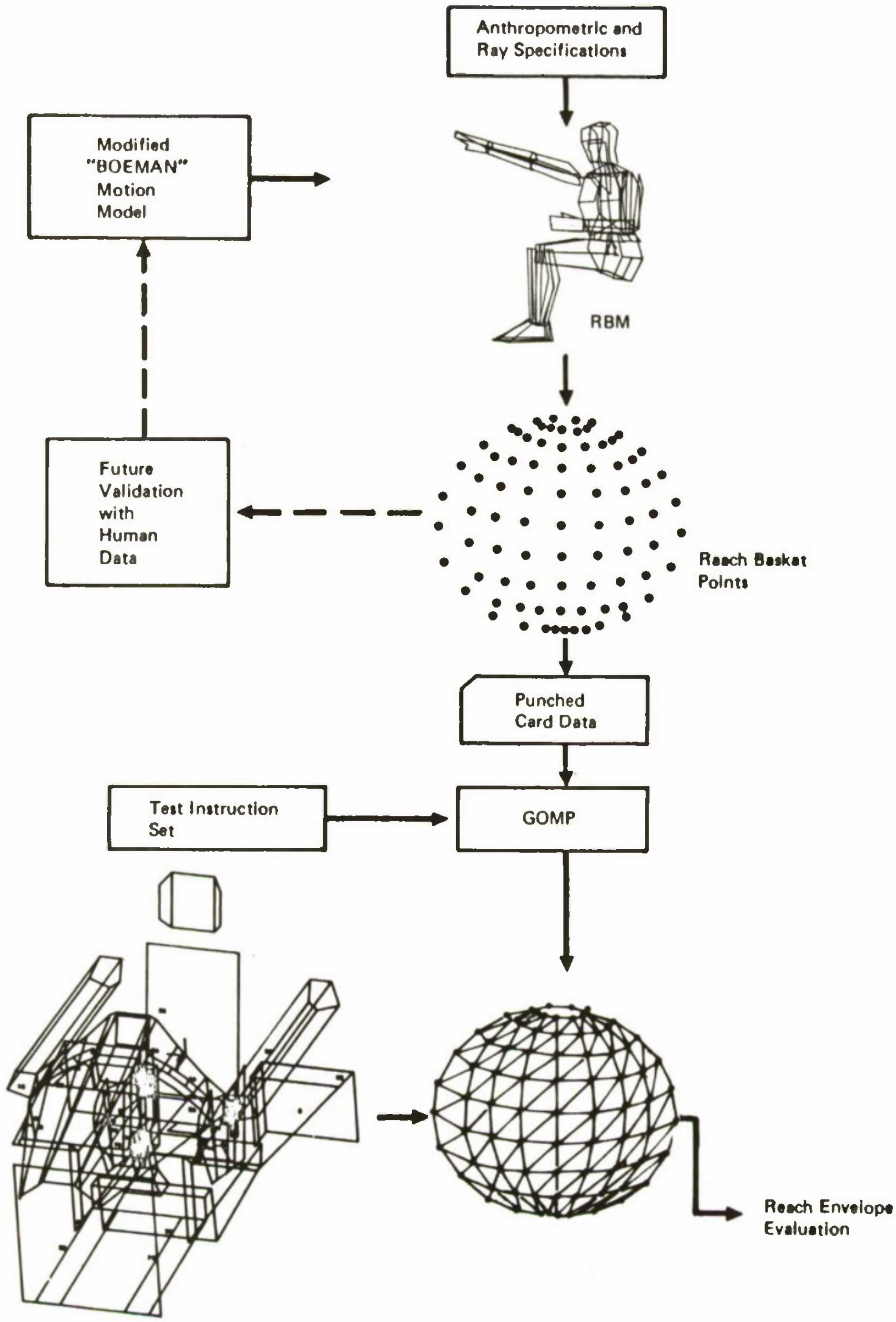

Figure 9. Reach envelope evaluation method.

TABLE 2

EXAMPLE OF THE TYPES OF RESULTS FROM THE EVALUATION OF THE A-7E COCKPIT WITH THE CGECPS

CONTROL/DISPLAY	REACH FEASIBILITY	PHYSICAL INTERFERENCE	VISUAL INTERFERENCE	COMMENTS
CONTROL STICK--AFT, NEUTRAL, AND FORWARD POSITIONS	OK	NONE		
ADI			NONE	
CATAPULT GRIP	OK	SLIGHT INTERFERENCE OF HAND SEGMENT WITH THROTTLE AT FINAL POSITION		THIS IS A GRAZING INTERFERENCE WHICH THE PHYSICAL INTERFERENCE AVOIDANCE ROUTINE (PIA) DID NOT DETECT AND IS NOT SIGNIFICANT.
LANDING GEAR HANDLE	OK, BUT 3RD % NEAR FULL ARM EXTENSION	NONE		CONTROL LOCATION SHOULD BE INDEPENDENTLY RE-EXAMINED (I.E., THE DESIGNER OR EVALUATOR SHOULD RE-EXAMINE THE LOCATION AS A CHECK ON THE BOEMAN RESULT).
LANDING GEAR POSITION INDICATOR			NONE	
SALVO JETTISON	3RD % CANNOT REACH	98TH % ENTERS PIA TO AVOID LANDING GEAR BUT STILL GRAZES IT IN PERFORMING TASK	NONE	CONTROL LOCATION SHOULD BE RE-EXAMINED INDEPENDENTLY.

be undertaken. Thus, an evaluation of the A-7E cockpit was undertaken as the first real test of the validity of the entire CGECPS. It was felt that such a test would provide a first indication of how well all the CGE developments had progressed to date, whether the developments should be continued and, if so, what modifications would be beneficial.

Data on the geometry of the cockpit of the A-7E were obtained from a large array of drawings kindly furnished by Mr. E. R. Atkins of the Vought Aeronautics Corporation. These geometry data were used to create 204 cockpit planes and 104 controls and displays. A perspective computer graphics view of the final geometry is shown in Figure 10.

Task sequences were established for 3rd, 5th, 95th and 98th percentile man-models to perform. Most tasks were performed assuming a locked shoulder harness condition. Obviously this is a rather conservative approach and it is not surprising that the 3rd and 5th percentiles had difficulty reaching some of the more forward and rearward controls.

However, comparison of the CGECPS results with A-7E crew interview data and other human engineering data indicates that they are generally correct for more than 80 percent of the tasks performed by the man-model. Furthermore, in those tasks where discrepancies occurred they are quite obvious to the evaluator in most instances. For example, when questionable physical interferences are identified, most often the body segments and/or crew station geometry involved in the interferences and the extent of the interference indicate to the evaluator that interference can be ignored. Table 2 gives some examples of the types of results obtained from the evaluation of the A-7E.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

There is a definite requirement in the crew system technology to be able to effectively, responsively, and economically evaluate the geometry of a crew station design at various stages during the DDT&E process. Present evaluation techniques such as drawing reviews, measuring devices and techniques,

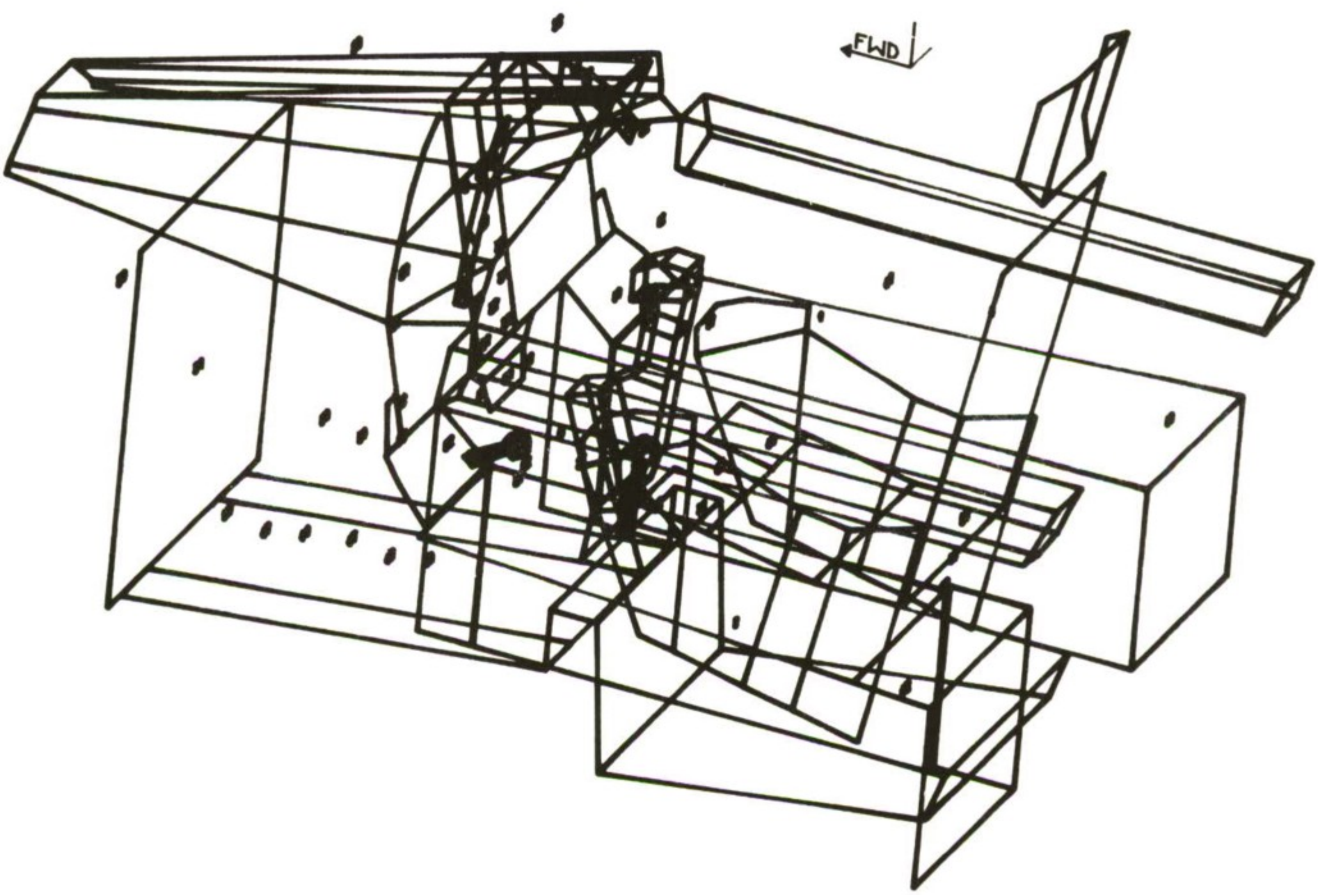

Figure 10. Perspective view of the modeled A-7E crew station.

mockups, simulators, and flight testing all contribute something to the evaluation process, however they all have limitations. For example, the drawing reviews and measuring devices and techniques are responsive and economical, but their effectiveness and thoroughness are limited. Simulators and flight testing are effective but they are costly and occur so late in the DDT&E process that any deficiencies they point out are difficult and costly to correct. Fome-Cor (Registered Trademark) mockups are presently the best compromise technique, however they are most often limited in their ability to be evaluated by a large enough sample size to ensure that the full variability in flight crew anthropometry has been accommodated.

The Cockpit Geometry Evaluation (CGE) program and its associated computer program system (CGECPS) were developed to improve the evaluation techniques. This program has developed a dynamic mathematical man-model, methods for describing and storing crew station geometry, task sequences, and crew anthropometry, and computer graphic routines. The man-model when exercised with this data determines reach infeasibilities, and physical and visual interference problems. In addition, a computer program has been developed which checks for crew station design compliance with selected geometry oriented military standards and specifications. A "levels of evaluation" concept has been developed which will increase the responsiveness and lower the cost of using computerized geometry evaluation techniques. Inherent in this concept is the development of a simple, but effective Reach Envelope Evaluation Method (REEM). The entire CGECPS was applied to the A-7E cockpit as its first pragmatic evaluation and validation. The results of this evaluation when compared with A-7E crew interview data and other human engineering data indicate that the CGECPS results were generally correct for more than 80 percent of the tasks performed by the man-model.

Two other pertinent results from the CGE program to date have come forth which could have an impact on future design and evaluation concepts. A comparison of the movement paths of trained operators in open regions and confined regions (e.g., fighter cockpits) indicates that significant differences occur. That is, the operator adapts to the confined environment, but what the impact of this is on either comfort or performance has not been ascertained. In addition, certain military standards requirements are in conflict. One of the primary conflicts involves forward reach in aircrew station with ejection seats. To provide adequate knee clearance for ejection the forward reach requirements of MIL-STD-1333 cannot be met.

The resolution of these types of problems should be one of the prime considerations of crew station designers and evaluators. In addition, the development of new techniques in the design and evaluation process should be furthered, especially the use of interactive graphic systems. The latter point cannot be overemphasized. Crew station designs have become extremely complex, yet the methods for designing them are basically an extension of the methods used to design World War I airplane cockpits, namely an engineer using a board, T-square, and triangles. The crew station design process has not kept pace with technology, and the aerospace industry, normally a leader in the application of technologies to the design process, has taken a backseat to the automotive and electronics industries.

In these industries we see significant developments in the application of computers and interactive graphics to the design of passenger compartments and circuits, respectively. Crew station designers in the aerospace industry should develop these same type of aids.

With a little imagination one can see the designer seated at a scope being able to recall data and geometric shapes from computer storage, having the computer routines check the design as it progresses with standards and specifications, having computer routines make supporting calculations on the spot, having an immediate hard copy made at any time, etc. Granted some efforts are being made along these lines, but they surely are not as advanced as they should be.

HIGH ACCELERATION COCKPIT DESIGN

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Abstract: *A configuration where the pilot is positioned with seat back at 25° aft of the vertical and legs elevated to the level of his buttocks, and with a seat back reclinable to 65° aft of the vertical for the high-g condition was chosen as the most promising to investigate for utilization in a high acceleration cockpit. To construct a final mockup of the seat configuration, tests were run to determine the mean hip pivot point of the seat back and the medial elbow locus so that reclining armrests could be constructed. The seat, which reclined by the use of actuators, was placed in a mockup somewhat representative of the F-15. Tests were conducted to establish crew station requirements, and these are discussed in this article. In conclusion, the configuration investigated was considered very functional for use in a high acceleration cockpit. Major problem areas which require further investigation are controls and displays, crew escape, and the unknown involved in the high-g environments as related to the seat back recline system.*

INTRODUCTION

Projected advances in aircraft structures and propulsion indicate that advanced air superiority fighter aircraft of the 1980s should be capable of sustained 8- to 12-g turns. Pilots in conventional fighter cockpits presently are limited to acceleration levels of five to seven g's in upright seats and with anti-g protection. In this position, the sustained acceleration levels are encountered from head to feet which can result in pilot blackout. To enable pilots to withstand the higher acceleration levels that will be encountered in these advanced fighter aircraft, new provisions, which will have a significant effect on the crew station design, will have to be incorporated into the cockpit.

Many factors affect a pilot's g tolerance level. These are body positioning relative to the g vector, rate of g onset, utilization and type of anti-g suit, pilot's experience and training, pilot's will to resist blackout by straining, and the pilot's physical condition and comfort. At acceleration levels beyond eight or nine g's, if the pilot is not positioned transverse to the g vector, he will most likely black out, even with anti-g suit protection. Therefore, to reduce possibility of blackout, the pilot should be in a semi-prone or semi-supine position. Shown in Figure 1 is the assumed optimum high-g seated position used in this program (Schroll, 1972). Because the high-g vector is perpendicular to the flight path of the aircraft, the g vector is shown offset 15° to allow for the assumed angle-of-attack of the aircraft. In the high-g environment, the pilot will need support so he will not encounter difficulty in controlling the aircraft. Areas of the body that will require support are the feet, thighs, buttocks, forearms and elbows, the torso, and the head.

Five configurations were studied that would place the pilot in the high-g seated position. These were conventional cockpit geometry with a reclining seatback, a rotating seat, a rotating cockpit, and two configurations that involved unique cockpit geometry with a permanent semi-supine seat and a semi-supine seat with reclining seat back. The configuration chosen to be the most promising was the semi-supine seat with reclining seat back (see Figure 2). This provided good overall external vision for both seat back positions and placed the pilot in a good position for high-g maneuvers.

In development of the semi-supine seat with reclining back, the following functional criteria were established as necessary guidelines: (1) the seat back should recline with no body sliding or scrubbing; (2) the control stick and throttles are incorporated into the forward part of the armrests; (3) the armrests, which provide forearm and elbow support in the high-g environment, should recline with the seat back in such a way that the forearms do not slide over the surface of the armrests; (4) all controls and displays must be visible and accessible; (5) the pilot must have adequate external vision for takeoff and landing and all phases of air-to-air combat; and (6) the configuration must accommodate the 5th through 95th percentile dimension ranges of USAF pilots. Current USAF geometry requirements were used as constraints to determine an optimum crew station configuration.

Using the above criteria to investigate this concept, a full-size mockup was constructed. This incorporated all cockpit

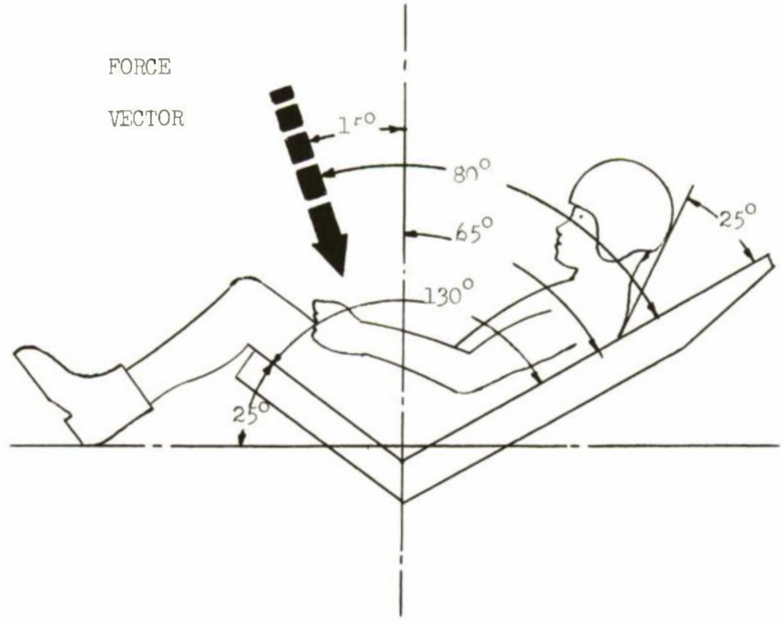

Figure 1. High-g seated position.

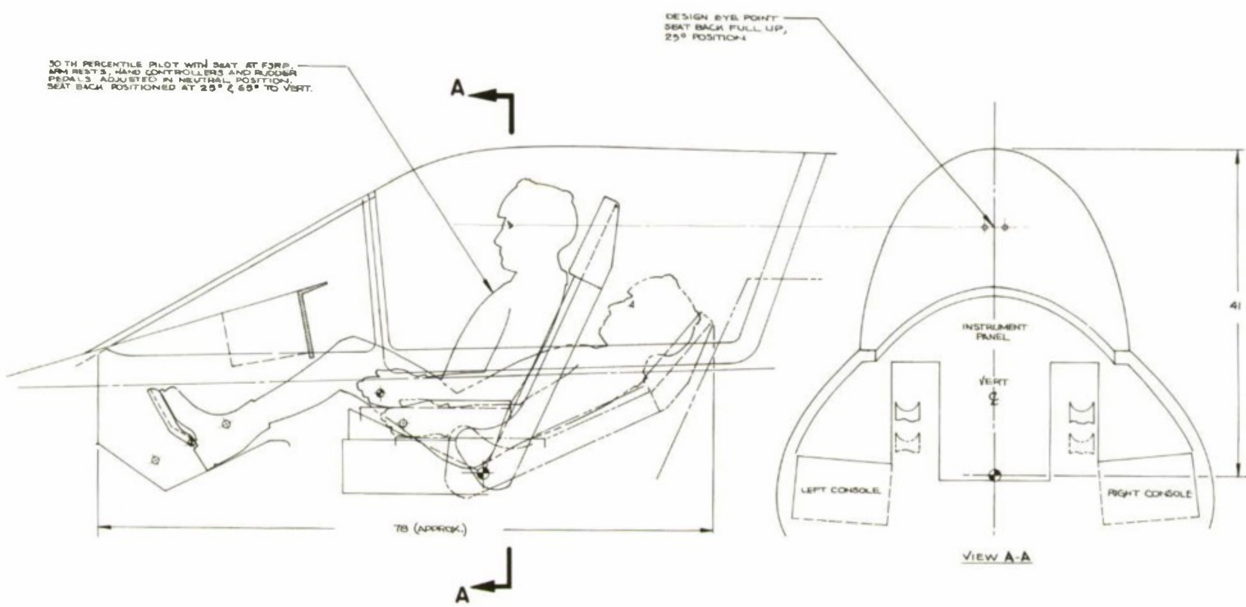

Figure 2. Semi-supine with reclining seat back configuration.

geometry and adjustments required so that: (1) the compatibility of the reclining seat, with the cockpit geometry could be determined; (2) the mockup would establish if the configuration would be a functional fighter aircraft cockpit; and (3) problem areas could be more easily anticipated. The high acceleration cockpit configuration was determined as a result of testing as many as 200 various sized subjects in the mockup. Shown in Figures 3, 4, 5, 6, and 7 are different views of the mockup.

SEAT DESIGN

The design of a seat system with reclining armrests and seat back involved many problems with cockpit geometry. As shown in Figure 2, this seating arrangement differed considerably from that of the conventional configuration, making it necessary to investigate all conventional requirements and either verify or establish new criteria. Following is a detailed analysis of each component of the seat system.

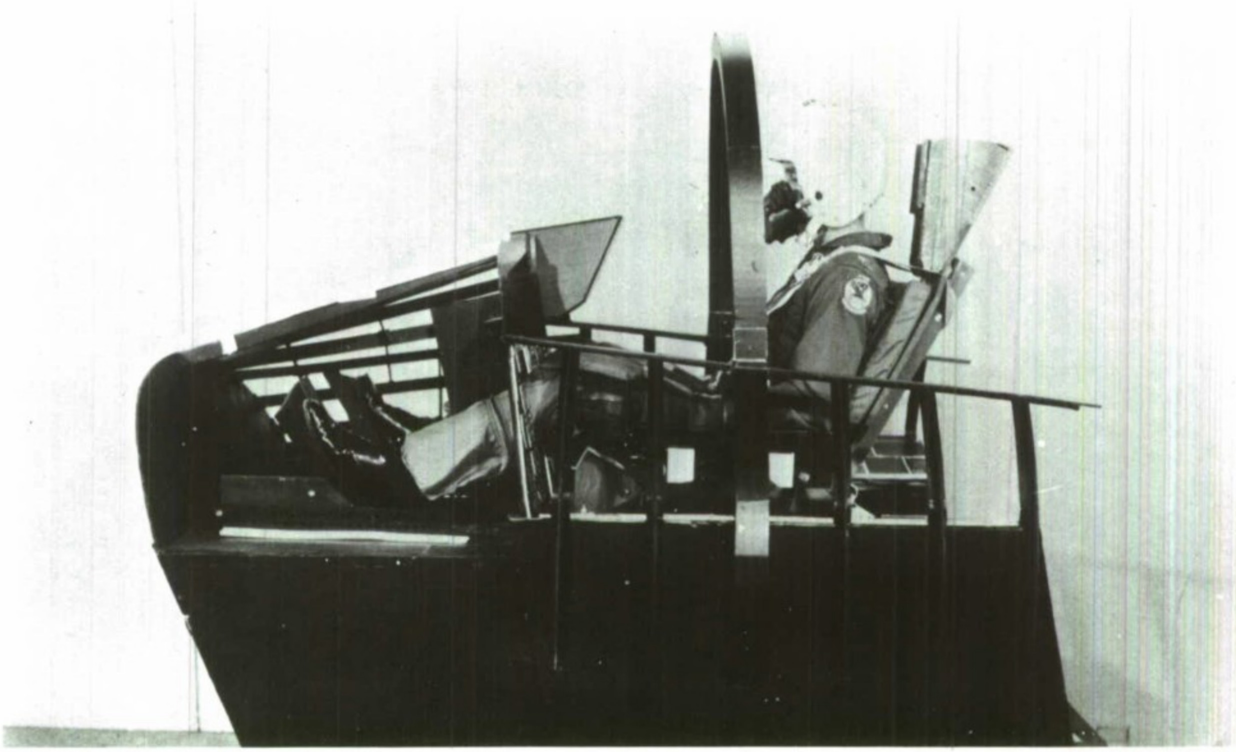

Figure 3. Mockup-seat back full up.

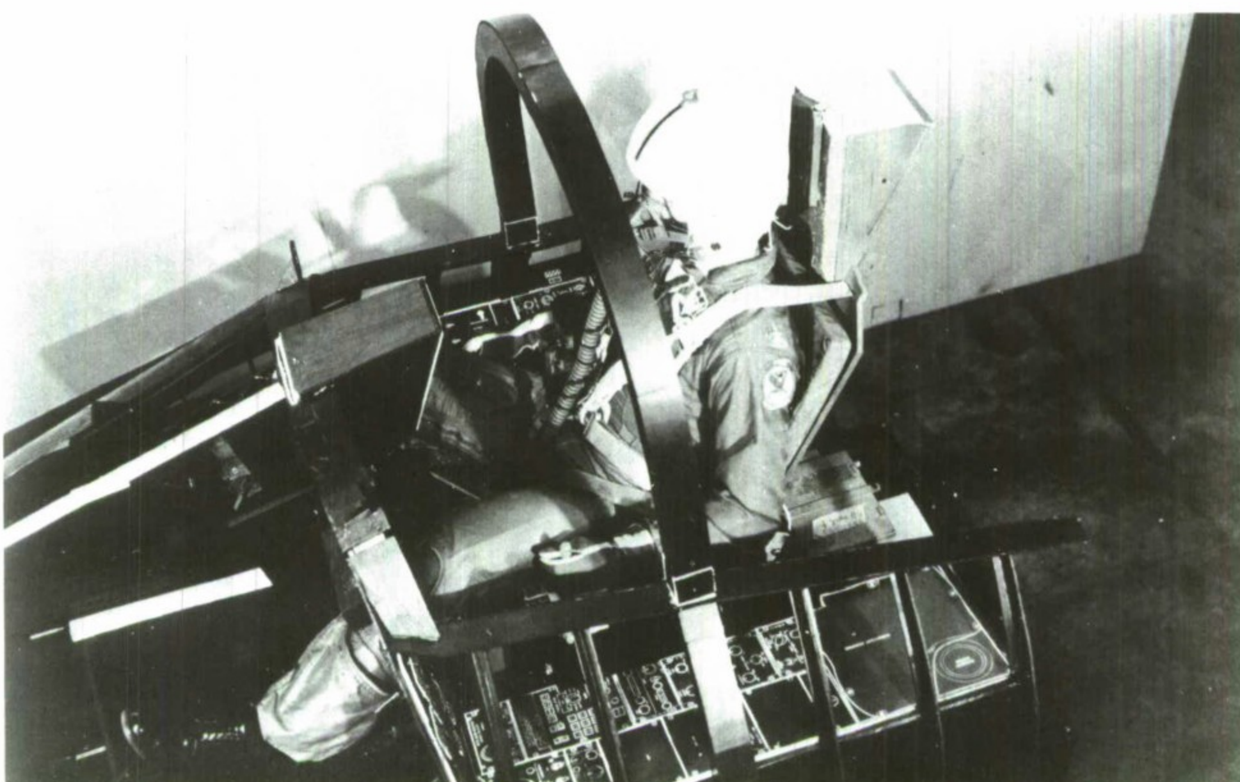

Figure 4. Mockup-seat back full up.

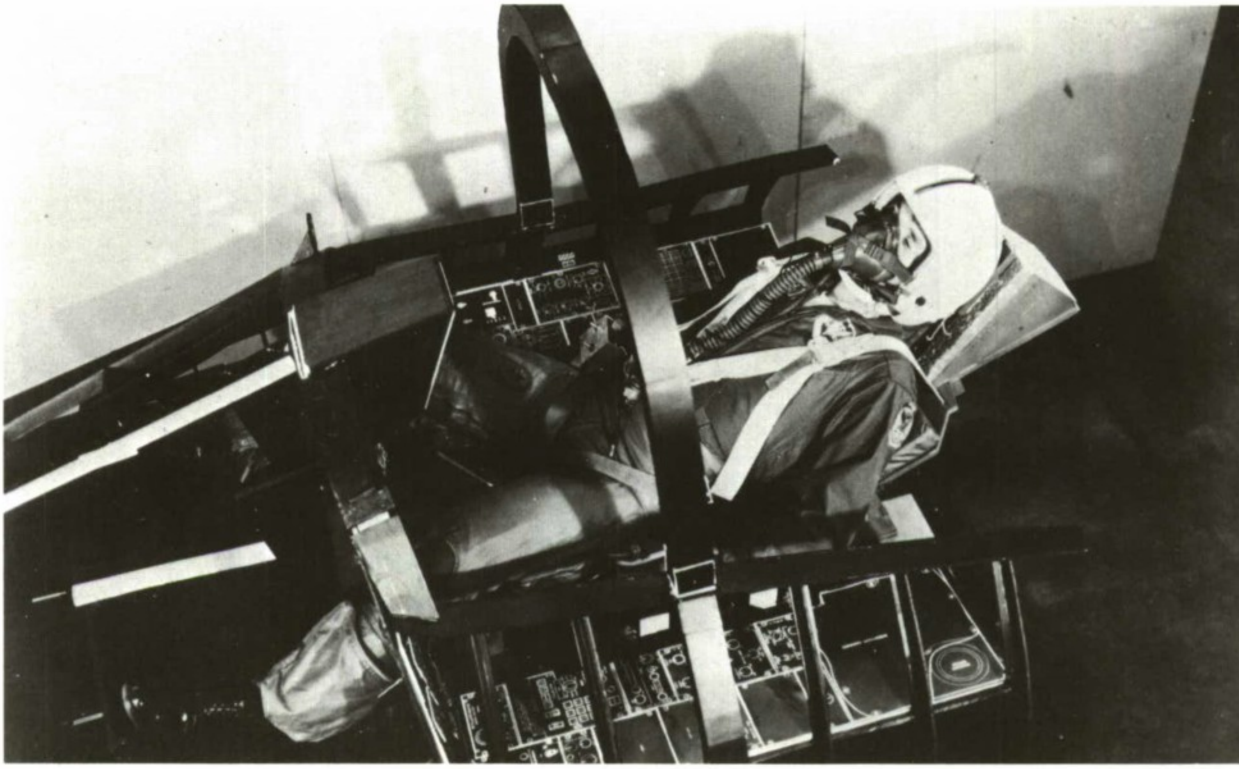

Figure 5. Mockup-seat back fully reclined.

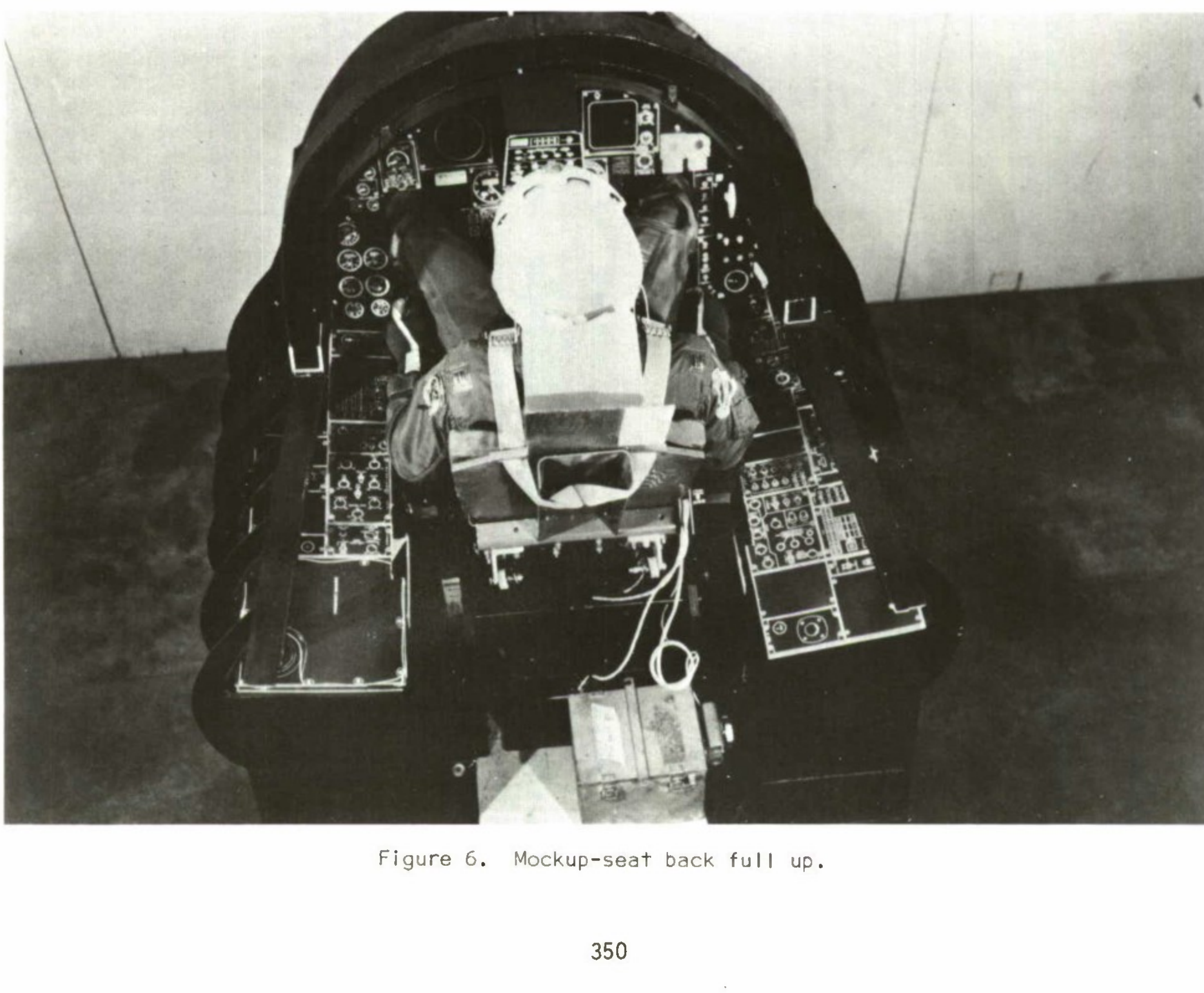

Figure 6. Mockup-seat back full up.

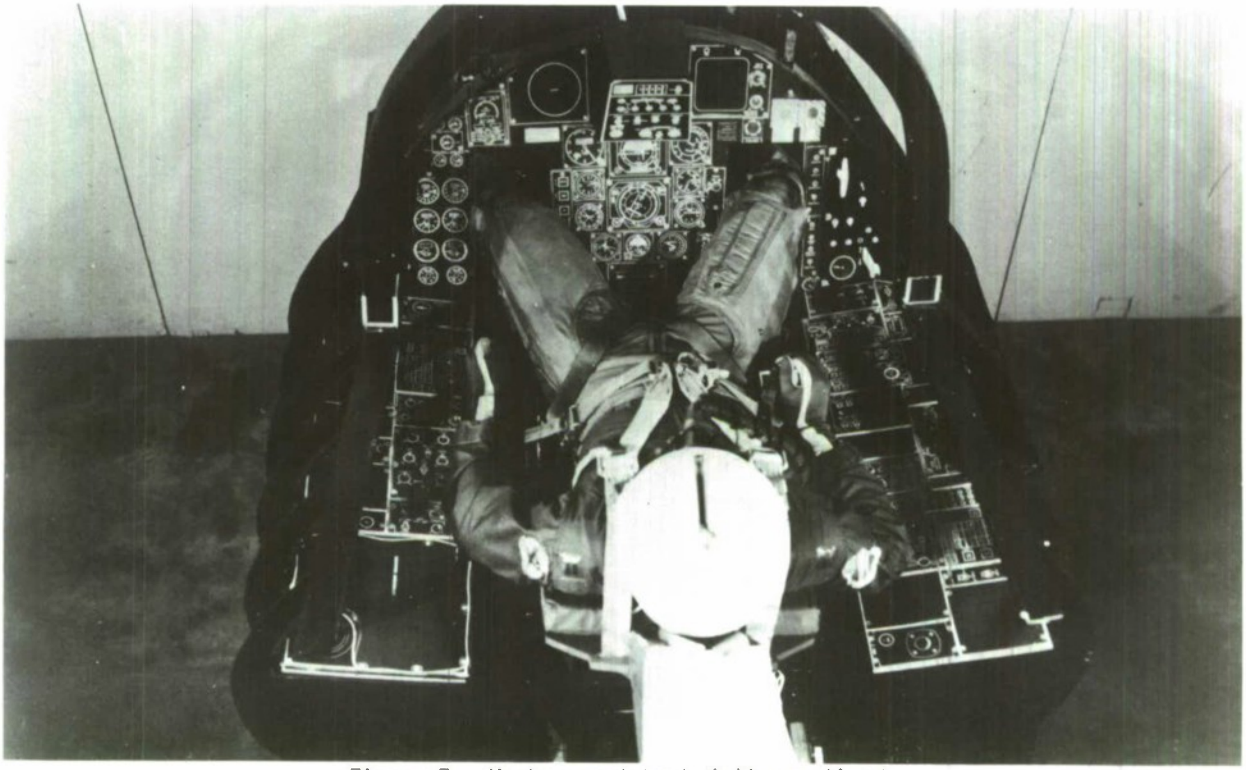

Figure 7. Mockup-seat back fully reclined.

HEADREST

The purpose of the headrest is twofold. During seat ejection, head support is necessary to prevent neck or spinal injuries. In this case, the headrest must be along the line of the seat back. Assuming that the seat is ejected when the back is in the full up position only, then the headrest should be parallel to the seat back tangent line for the purpose of seat ejection. The headrest would also restrict head movement if it were inclined forward while the seat back was in the full up position. As the seat back reclines, the headrest should rotate forward to support and position the head for forward vision during high-g maneuvers. Geometry requirements for the headrest as shown in Figure 8 were determined from the seat mockup using various subjects ranging from 5th through 95th percentile in sitting eye height. Initially, the headrest was built into the mockup at a fixed position and a headrest angle of 25°. After placing subjects of 5th through 95th percentile sitting eye height in the mockup, it was concluded that this headrest angle was adequate with the seat in the fully reclined position.

THE SEAT BACK

During the conceptual studies, it was determined that the seat back recline approach was the better method to place the pilot in the high-g position. Upon further investigation, it readily became apparent that pivoting the seat back about the seat reference point would cause a back scrub of three or four inches which is totally unacceptable. In designing the seat mockup, it was necessary to determine the location of an optimum pivot point of the seat back that would give minimum back scrub for all pilots. Since the human body rotates about the hip as the torso supinates, the seat back should also recline about the hip pivot point. For different size pilots, there will be different hip pivot point locations. Since the seat back can only rotate about one point, it was necessary to determine the location of a mean hip pivot point (MHPP) that would minimize back scrub for various size pilots. This was accomplished by a trial and error procedure in the seat mockup where the seat back pivot point was varied in relationship to the fixed seat reference point (FSRP). The MHPP was then eventually determined and the location was verified by reclining various sized subjects. As the torso rotates about the human body hip joint, more than a simple pivot point of rotation is involved. The centers of rotation of the hip joint move slightly aft as the torso rotates back (see Figure 9). A series of curves of hip pivot centers are described (Dempster, 1955). It must also be remembered that, although the location of the body hip pivot points does change in relationship to the seat, the FSRP does not by definition. This

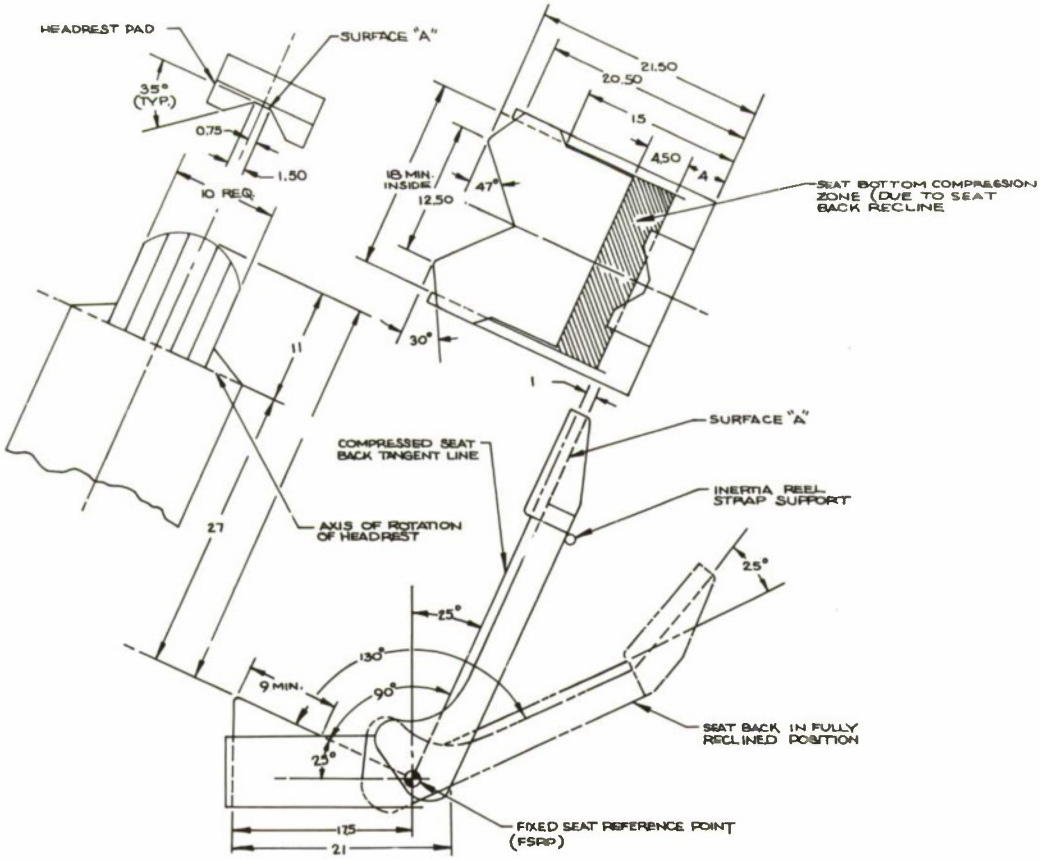

Figure 8. Seat geometry.

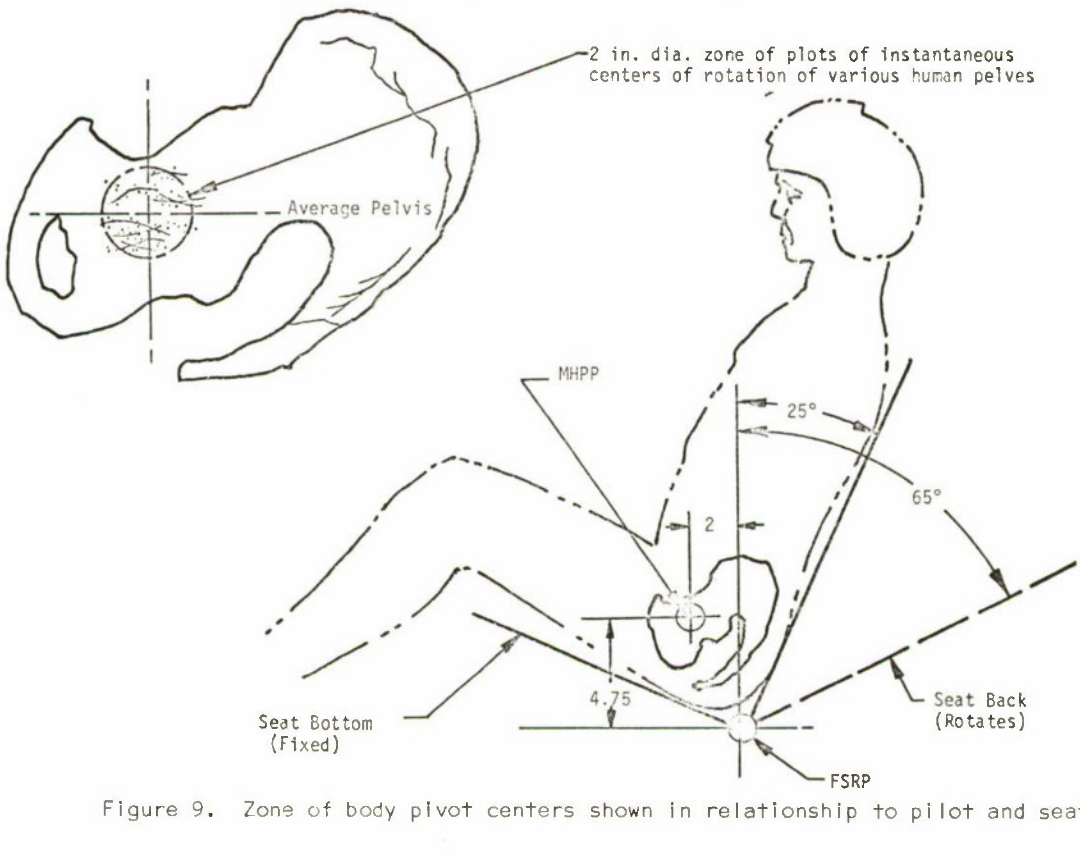

Figure 9. Zone of body pivot centers shown in relationship to pilot and seat.

means that the hip pivot point will move closer to the FSRP as the pilot experiences high g's. This is because the increased force due to the transverse acceleration of the aircraft will act upon the pilot compressing the pilot's buttocks and the seat cushions. Because the mockup can only represent the one-g case, and the amount of body hip pivot point movement is dependent upon the g levels encountered and the type and thickness of cushions utilized, the MHPP has been located for the one-g case throughout this study. In design of the actual aircraft seat or a seat used for high-g simulation studies, all these factors mentioned previously must be considered.

The seat was mocked up so that the seat back reclined about the MHPP which was located as dimensioned in Figure 9 so that this relationship between these points is fixed while the seat is in neutral position. Approximately 100 subjects have been supinated in this seat, and none experienced back or thigh scrubbing or sliding. This was a very good indication that the body hip pivot point could be anywhere within a one-inch radius of the seat MHPP and no back scrub would result.

The geometry of the seat back is similar to the conventional seat back in that a width of 18 inches is required and the seat back must be high enough to support the shoulders of a 95th percentile pilot. Structure is required at the sides of the pilot's hips for support. The interface of the seat back and bottom must be flexible yet provide adequate support of the buttocks throughout the range of seat back recline positions.

It was determined from the mockup that a vertical seat adjustment (the arm rests and mechanism are considered a part of the seat) of five inches would be more than sufficient to accommodate the 5th through 95th percentile, and no horizontal seat adjustment was necessary. In the mockup, the seat was adjusted vertically and not along a seat back tangent line at the angle of seat ejection as is common practice on ejection seat equipped aircraft. If the latter type of seat adjustment is provided, then the seat will move aft as it is adjusted to the UP position and forward as the seat is adjusted to the DOWN position. This will affect functional reach, seat-instrument panel interference, internal vision, and location and adjustment of the yaw axis controls.

SEAT BOTTOM

The first consideration in design of the seat bottom was the thigh rest angle. The small pilot would adjust the rudder pedals aft and the seat up, whereas the large pilot would do the opposite. It was evident that the thigh rest angle should be more than six degrees to keep the subject from sliding forward on the seat bottom during seat back recline and to provide support for the thighs. It is known that humans cannot bend with a hip flexure angle (the included angle of the seat bottom tangent line and the seat back tangent line) much less than 85° without experiencing undue leg and back muscle strain over a period of time. Therefore, it was evident that a thigh rest angle (the included angle between the seat bottom tangent line and the horizontal reference) greater than 30° would be unacceptable. This was determined from many various sized subjects in the seat mockup. It became a trial and error problem with different size subjects to determine the best overall thigh rest angle. A thigh rest angle of 20 to 25° was satisfactory to a majority of the subjects. Some of the larger subjects complained of inadequate thigh support; however, due to an instrument panel interference problem, the 25° position was selected.

In this concept, the legs straddle a large part of the instrument panel, thus the part of the seat bottom between the legs must be cut away so as not to obstruct visibility of the instrument panel (see Figures 10 and 11). This is especially a problem when the seat is adjusted to its highest position to accommodate the small pilot. The length of the seat bottom is dependent on interference with the instrument panel. It is for these reasons the seat bottom is an unusual shape (see Figure 8).

ARMREST DESIGN

As the seat back reclines, the arms would also move down and aft. Since each person would have a different curve of elbow travel, it was necessary to set up a test to determine a mean curve of elbow travel that would accommodate pilots with 5th through 95th percentile dimension ranges of height and weight. A test was set up to determine a seat with reclining armrests that would move to the proper vertical heights in relation to the seat back angle as the seat back reclined.

The seat was constructed on the basis of the results of this test. Next, a more elaborate test was set up to determine the curve precisely. A 35-mm camera was placed at the left side of the seat. Each subject (45 in all) sat in the seat and adjusted the armrests to the vertical height he desired. Photographs were taken of each subject's left arm as the seat back reclined at ten-degree intervals. After vertically transposing all the elbow curves to correct for vertical armrest adjustment so that they began at the same height, a zone in which the curves were scattered uniformly was described (see Figure 12).

Since the average armrest height, stature, and weight percentile dimensions were close to the 50th percentile, it can be stated

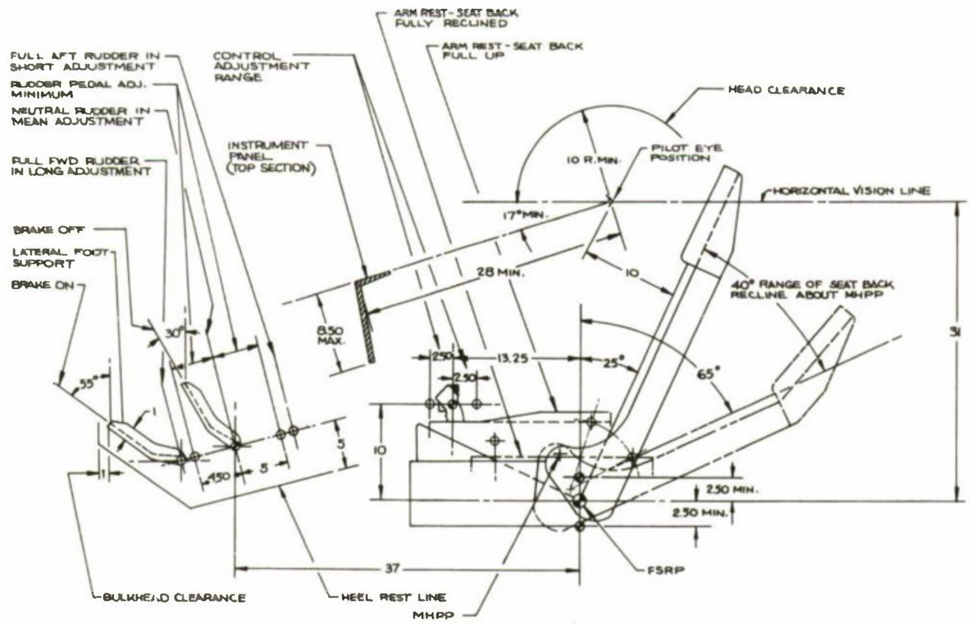

Figure 10. Basic cockpit dimensions.

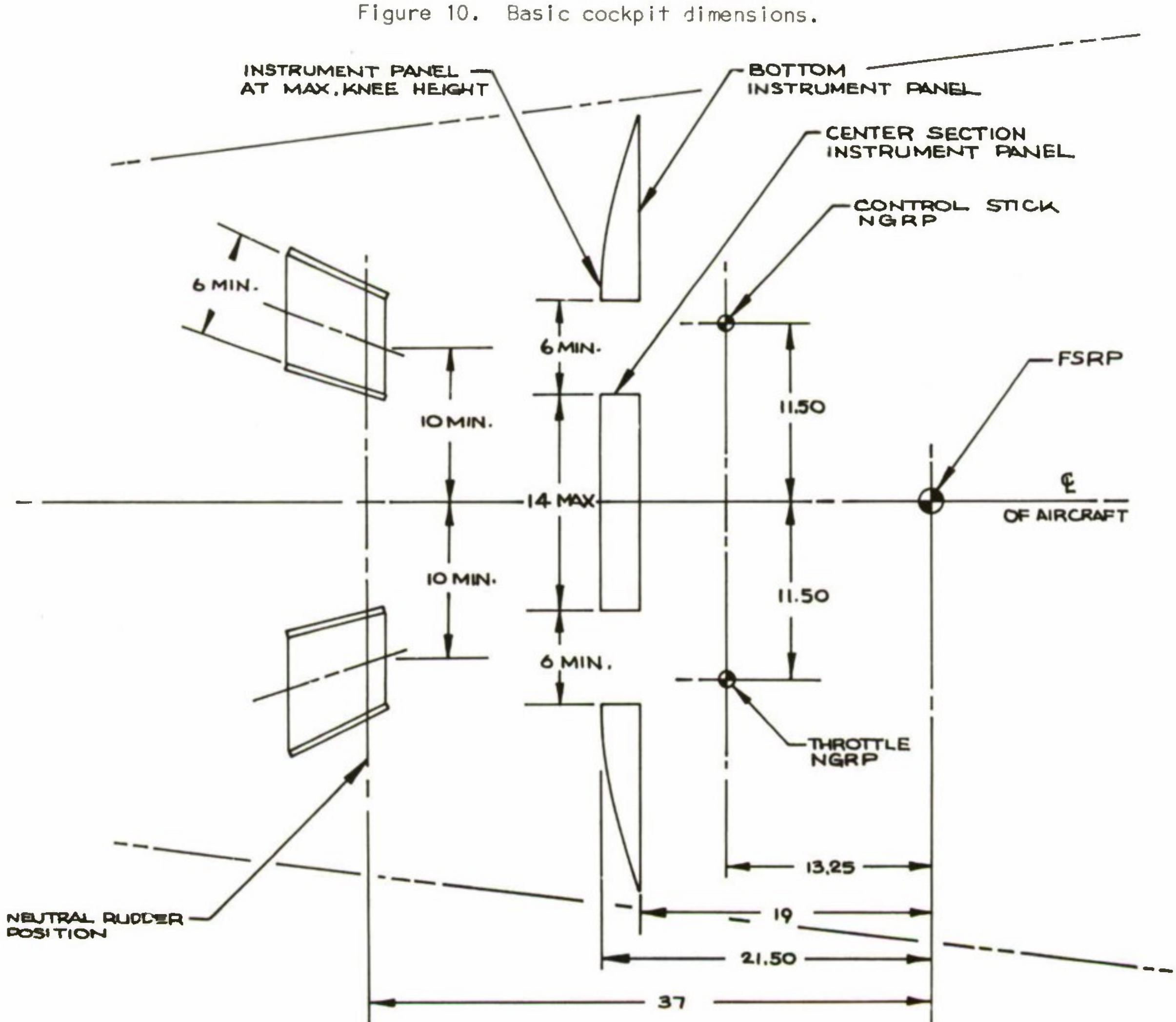

Figure 11. Basic cockpit dimensions (top view).

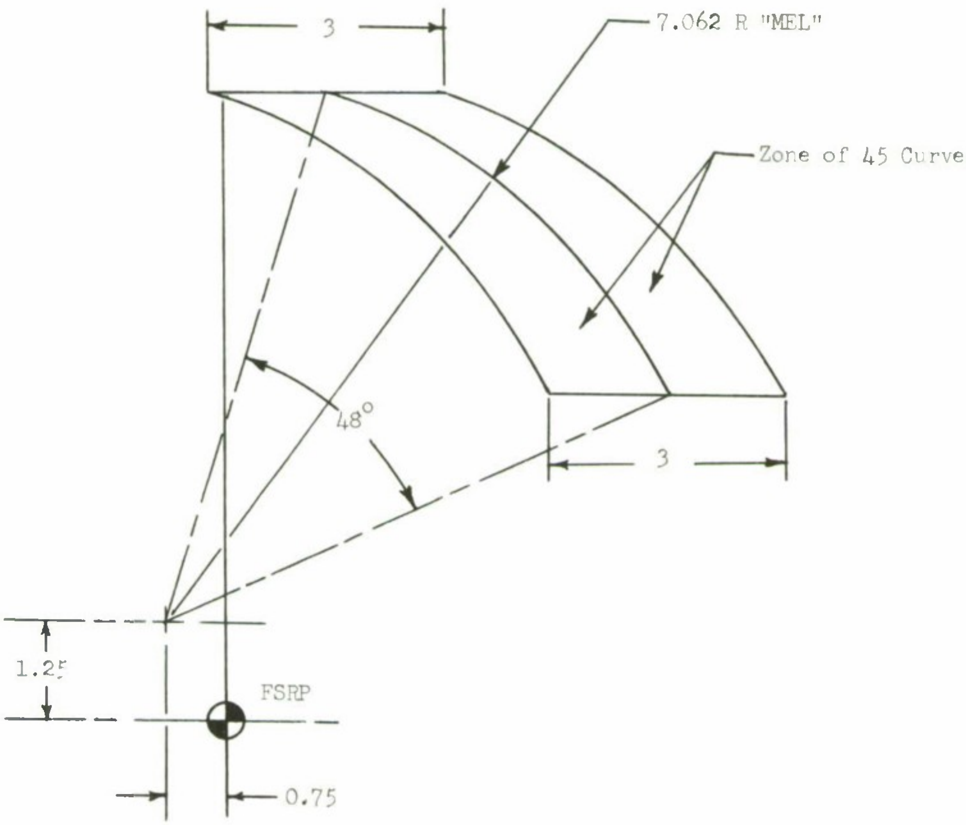

Figure 12. Zone of elbow loci of 45 subjects with medial elbow locus (MEL) illustrated.

with a reasonable degree of certainty that the curve that divided this zone in half would be the medial elbow locus (MEL). These anthropometric dimensions should most strongly influence the subject's elbow locus curve. It was also important to insure that a representative sample of these dimensions was used in the test. Figure 13 is a graphic illustration of the random sampling of stature, weight, and armrest height percentile of the subjects utilized in the test.

The seat and armrests were mocked up from the dimensions determined from the tests, and with the adjustments provided, almost 100 subjects have been supinated in the mockup. There is a very slight change of elbow position with some subjects, but the armrest configuration does provide the required forearm support for most subjects. The adjustment ranges as determined from this test were armrests, three inches vertical, and hand controllers, five inches horizontal. Figure 14 outlines the geometry requirements of the armrest configuration.

HIGH-g CONTROL REQUIREMENTS

PITCH AND ROLL CONTROL

When the seat back reclines for the high-g environment, the pilot's arms will be supported by the armrests. Because of his immobility at high g's, the pilot is limited to the controls he has at his fingertips, and his feet. It is necessary to determine what controls the pilot will need while in this high-g position. These controls should be arranged so that their shape and position can be recognized by "feel," since the pilot must maintain visual contact with the enemy aircraft. A review of the state of the art in the sidearm hand controllers (DeBoy, 1964; Rhoads, 1970) indicated that a two-axis sidearm hand controller as opposed to a center control stick or a three-axis sidearm hand controller was the most feasible approach to providing control inputs.

YAW AXES CONTROL

As on present fighter aircraft, yaw axes control should be foot operated. With the seat back full up or fully reclined in this seated configureation, it is very difficult, if not impossible, to move the rudder pedals back and forth the conventional 6.5 inches. This can be accounted for because of the larger thigh rest angle and the large external forces involved in the high-g environment. In the high-g environment, yaw axes control inputs would be accomplished by pivoting the ankles rather than leg movement to

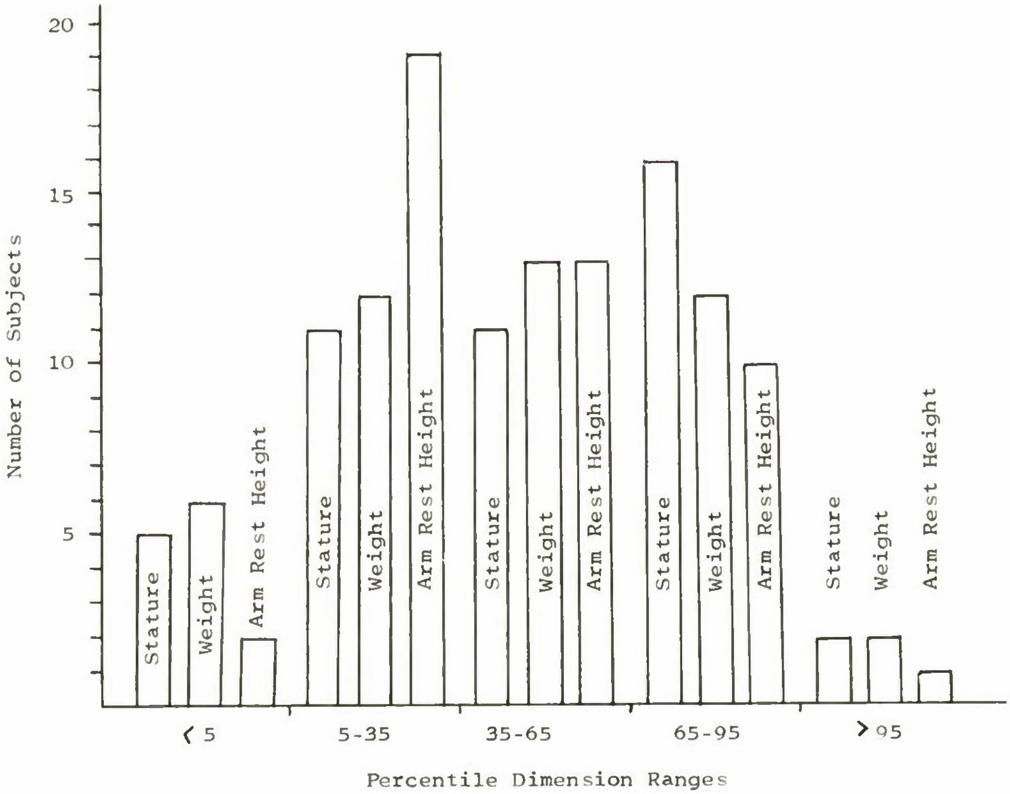

Figure 13. Comparison of percentile dimensions of 45 subjects.

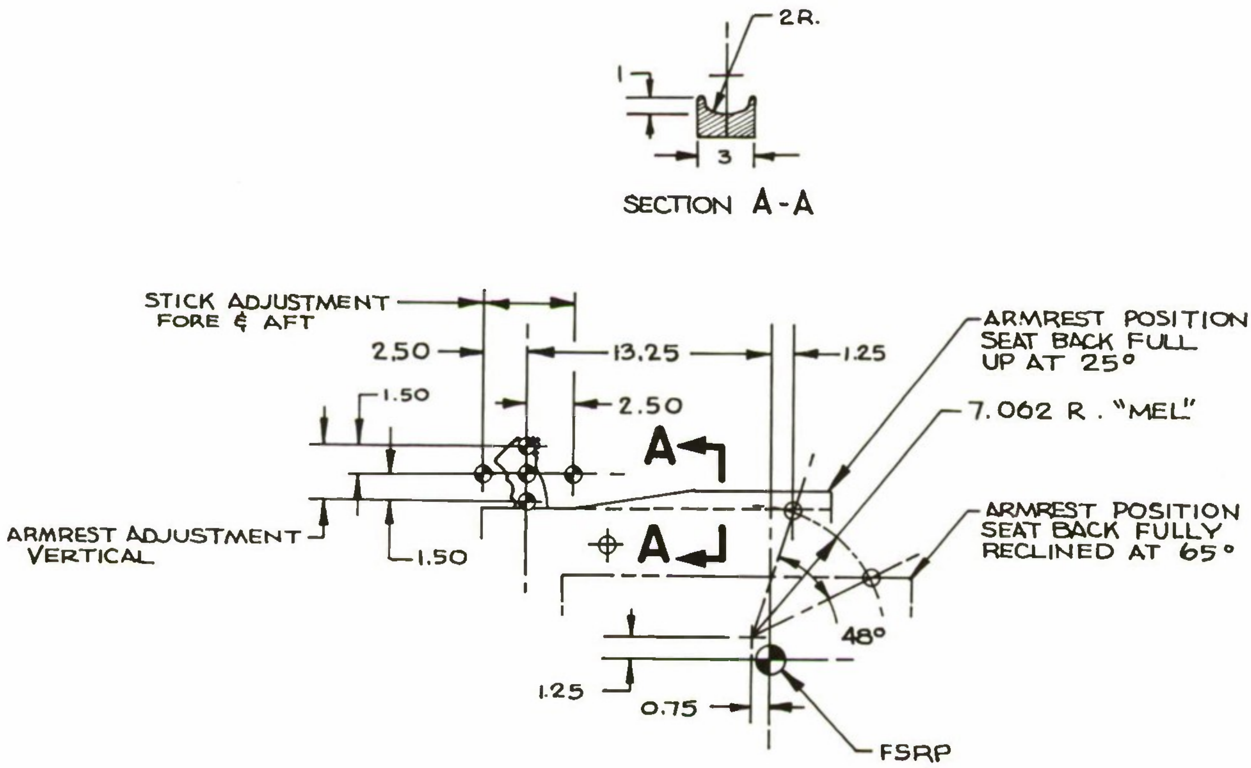

Figure 14. Armrest geometry requirements.

move the pedals fore and aft along the heel rest line. For other flight conditions, yaw axes control would be by the conventional manner, but pedal travel would have to be reduced. Further study is necessary to determine the amount of travel versus the force "feel" system required. Vertical and lateral support for the feet should be provided in the high-g environment.

POWER PLANT CONTROLS

The throttle(s) and some associated power plant controls are needed by the pilot in high-g turns. It is, therefore, necessary to locate these controls at the pilot's fingertips on the left armrest. The throttle(s) must be designed so that all the external forces involved do not cause inputs that the pilot does not desire.

OTHER CONTROLS

It is anticipated that the pilot will need these other controls on the side armrests at his fingertips: pitch and roll trim; manual firing, rockets, and guided missiles; applicable aerodynamic control devices (such as the speed brake); emergency controls (such as seat ejection); power augmentation; seat back recline override switch; and microphone switch. On the basis of mission/subsystem requirements of this fighter aircraft when developed, the need for these controls or other controls not mentioned will be determined.

VISION REQUIREMENTS

EXTERNAL VISION

In air-to-air combat maneuvers, the pilot relies mainly on visual tracking of the enemy aircraft. In this way, the pilot can determine what maneuver he must accomplish in order to gain the advantage over the enemy aircraft. Should the pilot lose visual contact with the enemy aircraft, he would then be forced to proceed with a defensive maneuver to re-establish visual contact and to keep the enemy aircraft from gaining the advantage. It is therefore important that external vision provided in the high acceleration cockpit be the best possible for the 25- and 65°-seat back positions.

Because this type of fighter aircraft will land and take off at high angles of attack, and because the pilot will need maximum over-the-nose vision as he closes in for gun attack, 17° over-the-nose is required. Rearward vision is also necessary. It is a requirement that the pilot be capable of rolling his head from one side to the other while in the high-g environment so that he can look horizontally to either side with both eyes. This requires the canopy to extend further down and aft than that of the conventional fighter cockpit.

VISION IN THE HIGH-g ENVIRONMENT

A high acceleration cockpit would be of little advantage to the pilot if he could not maintain visual contact with the enemy aircraft while in the high-g environment. While much study is needed to more fully understand visual changes encountered by the pilot due to sustained transverse acceleration, certain facts can be pointed out on the basis of past studies. Perhaps the biggest problem is that of the eyes tearing; the tearing rate increases with higher g levels (Smedal, 1960, 1963). Should the head be in a position that did not allow the tears to drain from the eyes, the pilot's vision would be blurred due to the liquid pooling in the eyes. Distortion of the cornea and eyeball also causes some blurring of vision. As g levels increase, a pilot would experience grayout or a gradual loss of peripheral vision (Smedal, 1963), and he would have what is termed tunnel vision. This will decrease the pilot's field of view, meaning the pilot will have increased difficulty in maintaining visual contact with the enemy aircraft. If the g level were too great for the pilot to withstand, he would black out (total loss of vision) and loss of consciousness would then follow. Currently, it is anticipated that supination of the pilot and proper support of his head will enhance his vision at acceleration levels up to nine to ten g's sufficiently, so that the previously mentioned problems will not interfere with his visual tracking. With increasing accelerations to 12 g's, the pilot's vision gradually deteriorates, and eventually visual tracking is not possible.

HIGH-g INFORMATION REQUIREMENTS

Because the pilot must maintain visual contact with the enemy aircraft while in air-to-air combat, because the pilot's vision will be degraded by the high accelerations, and because the pilot's head will be too far aft of the instrument panel when the seat back is fully reclined, conventional warning indicators will probably be inadequate. A potential solution to this problem is to incorporate a voice warning system (Kemmerling, 1969) into the cockpit.

THE SEAT BACK RECLINE SYSTEM

To afford the pilot maximum external vision at all times, the seat back should only begin to recline when absolutely necessary. For acceleration levels of very short duration, the pilot may not want the seat back to recline. This would require a seat

back recline override switch. It may be advantageous to provide some means for programming in the recline system so that individual pilots can preset the seat back to begin reclining at a desired g level and be fully reclined at a higher preset g level.

Even with a fighter aircraft which incorporates a high acceleration cockpit, the pilot may still be the limiting factor in high-g encounters. The pilot will be limited by the rate-of-g onset, and the time duration of the high g's. Both of these factors which would limit the pilot would not affect the aircraft.

CREW ESCAPE

At this time there are too many unknown factors involved to permit specifying the best crew escape system. The capsule (nose or pod) and ejection seat are both potential systems. The major drawback of the ejection seat is integration of this system with a high-g seat with reclining seat back. It may be structurally impractical to attach ejection guide rails to the seat back, so that they recline and upon ejection are pre-positioned to guide the seat out of the cockpit. On the other hand, the capsule weight penalty and cost could be limiting factors in its application.

CONCLUSIONS

Positioning the pilot transverse to the high acceleration vector is a feasible method of providing high-g protection for the pilot, and the configuration investigated in this program is considered a good approach to this concept.

Additional exploratory development effort should be applied to the high acceleration cockpit configuration resulting from this program, with emphasis on the major problem areas of controls, displays, crew escape, and the seat back recline system.

REMARKS

Experience gained during this program demonstrated that a full scale mockup incorporating all adjustments is essential if realistic crew station requirements are to be developed. Also, too much reliance has been placed on the use of body dimension percentile data to determine crew station requirements, especially those resulting from kinematic relationships between man and machine. Testing with a large random sample of subjects familiar with the type of crew station involved may uncover significant problems which would have to be resolved in order to have a satisfactory crew station.

The application of existing cockpit standards and requirements is only a partial solution to developing functional crew stations for future fighter aircraft. Cockpit design is highly sensitive to changes in mission requirements and advances in equipment, and consequently, new design criteria and guidelines are needed to provide the most effective crew stations.

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MULTIFUNCTION DISPLAYS--THEIR ROLE IN THE COCKPIT

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Abstract: *Considerable effort has been and is being undertaken in the development, design, and production of multifunction cathode ray tube (CRT) displays. This paper presents a descriptive overview of the multifunction display--what it is and how its use enables flight crew members to improve their performance while decreasing their workload.*

The multifunction display's primary role is to provide the flight crew with various selectable presentations of integrated flight parameters and sensor outputs. Multifunction displays are categorized by display dimension rather than by specific flight parameters. The three basic display dimensions are the horizontal plane, vertical plane, and the operator-display communication plane. For instance, the multifunction display for the horizontal plane would integrate radar, map, and horizontal situation indicator information into one display, dispensing with the use of a radar scope, a bearing distance heading indicator (BDHI) or a horizontal situation indicator (HSI), and manually held navigation charts. For the vertical plane, a multifunction display would integrate attitude, airspeed, altitude, and command cue information into a sensor display such as a forward looking infrared (FLIR) television display. For the communication plane, the multifunction display would be used for central control and information exchange between the multifunction display systems and the operator.

As the aircraft and their missions continue to become more complex, the information display, processing, and control demands also grow in both complexity and numbers. The one instrument-one display parameter instrument concept seriously affects the pilot's workload and his capability to assimilate the information being presented. To help improve this situation, the multifunction display concept has been developed. It offers the following advantages:

- *Increased flight orientation.* The integration of many flight parameters into a central display provides an overall awareness of the aircraft's situation.

- *Reduction of crew station workload.* This integration eliminates the need for separate instruments displaying only a few flight parameters resulting in the following: (1) reduction of the number of instruments to scan; (2) reduction of manual actions for controlling these instruments; and (3) elimination of the mental integration of the separately displayed flight parameters to obtain an overall instantaneous flight situation.

- *Additional new flight information.* With the many flight parameters available to the multifunction display, predictive flight information such as flight path vectors, trend vectors, predicted attitude penetrations, and time interceptions can be derived. The realm of predictive information and its potential is just now being explored.

- *Additional new information transfer dimension.* Since the display system is flexible, auxiliary information in either graphical or alphanumeric form can be displayed separately or overlayed on an integrated display mode. A typical display could be energy management, or real-time CRT annotations of a projected map display providing targeting and tactical navigation information.

Many multifunction displays are presently being used or evaluated. In most cases only one of the dimensional planes is used instead of a multifunction display set that covers all three dimensional planes. Tables 1 through 3 provide a list of the multifunction displays which provide display for the horizontal, vertical, and control/display (communication) planes respectively. Also the display function and the aircraft or program in which the multifunction display is being used or evaluated are contained in these tables.

There is a potential problem in using only one multifunction display which provides only one-dimensional plane information. There could be an increase rather than a decrease of the operator's workload because the multifunction display is just another instrument in

TABLE 1

HORIZONTAL SITUATION MULTIFUNCTION DISPLAY

FUNCTION	USE
1. RADAR/PROJECTED MAP MATCHING	1. HELICOPTER EVALUATION BY U.S. ARMY-HELMS RADAR; EUROPEAN PANAVIA MRCA AIRCRAFT (MULTI-ROLE COMBAT AIRCRAFT)
2. TACTICAL AND NAVIGATIONAL ANNOTATION OF COMBINED CRT/PROJECTED MAP DISPLAY	2. USAF F-111D AND FB-111; MRCA (SEE FIGURES 4 AND 5--F-111 HORIZONTAL SITUATION DISPLAY)
3. PROJECTED MAP DISPLAY	3. USAF/USN A-7 AIRCRAFT: USAF F-111D FB-111; MRCA
4. THREAT/NAVIGATION ALL ELECTRONIC DISPLAYS	4. USN F-14; USAF F-15; USAF F-111D
5. ALL ELECTRONIC NAVIGATION DISPLAY	5. LOCKHEED L-1011 AIRBUS (SEE FIGURE 6--COCKPIT INSTALLATION)
6. ELECTRONIC HORIZONTAL INDICATOR DISPLAYS	6. USAF CRT-HSI EVALUATION PROGRAM (SEE FIGURE 7); AIRLINES ACTIVELY DEFINING SPECIFICATIONS THROUGH ARINC (AERONAUTICAL RADIO, INC.)
7. SENSOR TELEVISION DISPLAY	7. USAF F-111D AND FB-111 (SEE FIGURE 8)

TABLE 2

VERTICAL SITUATION MULTIFUNCTION DISPLAY

FUNCTION	USE
1. ELECTRONIC ATTITUDE DIRECTOR INDICATOR (EADI)	1. USAF B-1 BOMBER; USN A-6 AIRCRAFT; USAF F-111D; BOEING SUPERSONIC TRANSPORT AVIONICS EVALUATION PROGRAM; NASA STOLAND PROGRAM; SPECIFICATIONS BEING PREPARED BY THE AIRLINES ARINC COMMITTEE
2. SENSOR TELEVISION DISPLAYS	2. USAF B-42; USAF B-1; USAF F-111D

TABLE 3

CRT CONTROL/DISPLAY MULTIFUNCTION DISPLAY

FUNCTION	USE
1. NAVIGATION STATUS/CONTROL DISPLAY	1. LOCKHEED L-1011; McDONNELL DC-10; BOEING SUPERSONIC TRANSPORT AVIONIC EVALUATION PROGRAM
2. GRAPHICAL AND TABULAR DATA DISPLAY	2. PANAVIA MRCA AIRCRAFT; BOEING SUPERSONIC TRANSPORT AVIONICS EVALUATION PROGRAM

that the operator must still derive the remaining dimensional planes manually from the other flight instruments. Hence, the multifunction display can be another instrument burden to add to the operator's list.

The "I" (In-line Concept) of a multifunction display set that provides the three-dimensional display planes is shown in Figure 1. This concept is similar to the "T" concept for the arrangement of the standard electromechanical instruments (the HSI, and ADI making up the leg of the "T," with the airspeed indicator and altimeter being the sides of the "T"). Figure 2 shows the arrangement of the displays for the "I" concept. The primary and secondary functions for the vertical situation multifunction display (vertical dimensional plane) and the horizontal situation multifunction display (horizontal dimensional plane) are shown in Figure 3.

The multifunction display set consists of five units--three display units, and two electronic units. The top display unit is a five-inch by seven-inch vertical situation display. The middle display unit is the horizontal situation display. The display size that is becoming standard is either a seven-inch diameter (for combined CRT/projected map displays) or the seven-inch by seven-inch (for the electronic display). The third unit is the controller unit which provides status display on a CRT screen of three-inch by four-inch and provides control by use of a keyboard. The keyboard uses function keys rather than typewritten-type keys. Also selector keys are located along the side of the CRT display (the long dimension). These selector keys enable the operator to choose from various selections presented to him on the display. Function and selector keys enable an easy communication response by the operator. A typical use of such a keyset would be as follows. A function key could be labeled "targets." When the key is depressed, a listing of targets from which to choose would appear on the display. After one of the targets listed has been selected, a navigation display would be overlayed on the projected map display to provide the route to the target and the associated enroute threats. A second listing on the controller display could be a listing of the ordnance for selection, or energy management displays based on the target selected.

The heart of the "I" concept is the display management computer. This computer contains the moding and formating of the displays,

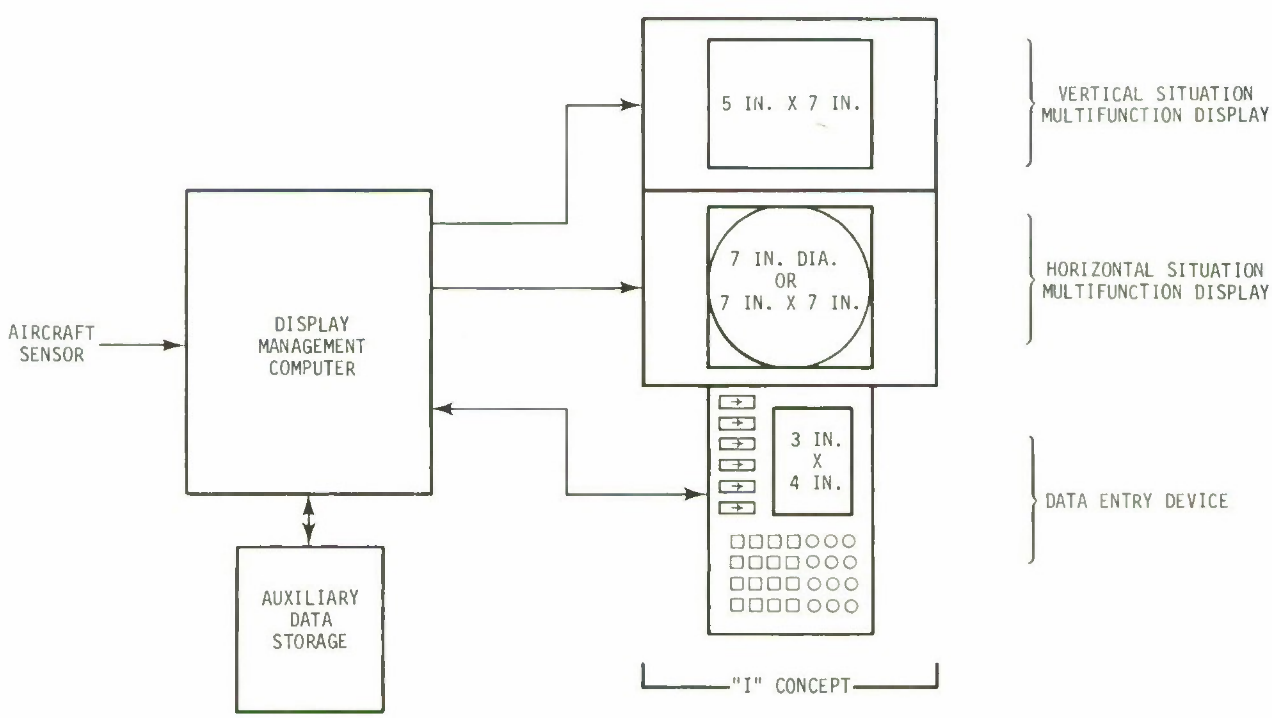


Figure 1. "I" Concept block diagram.

Figure 2. "I" Concept display arrangement.

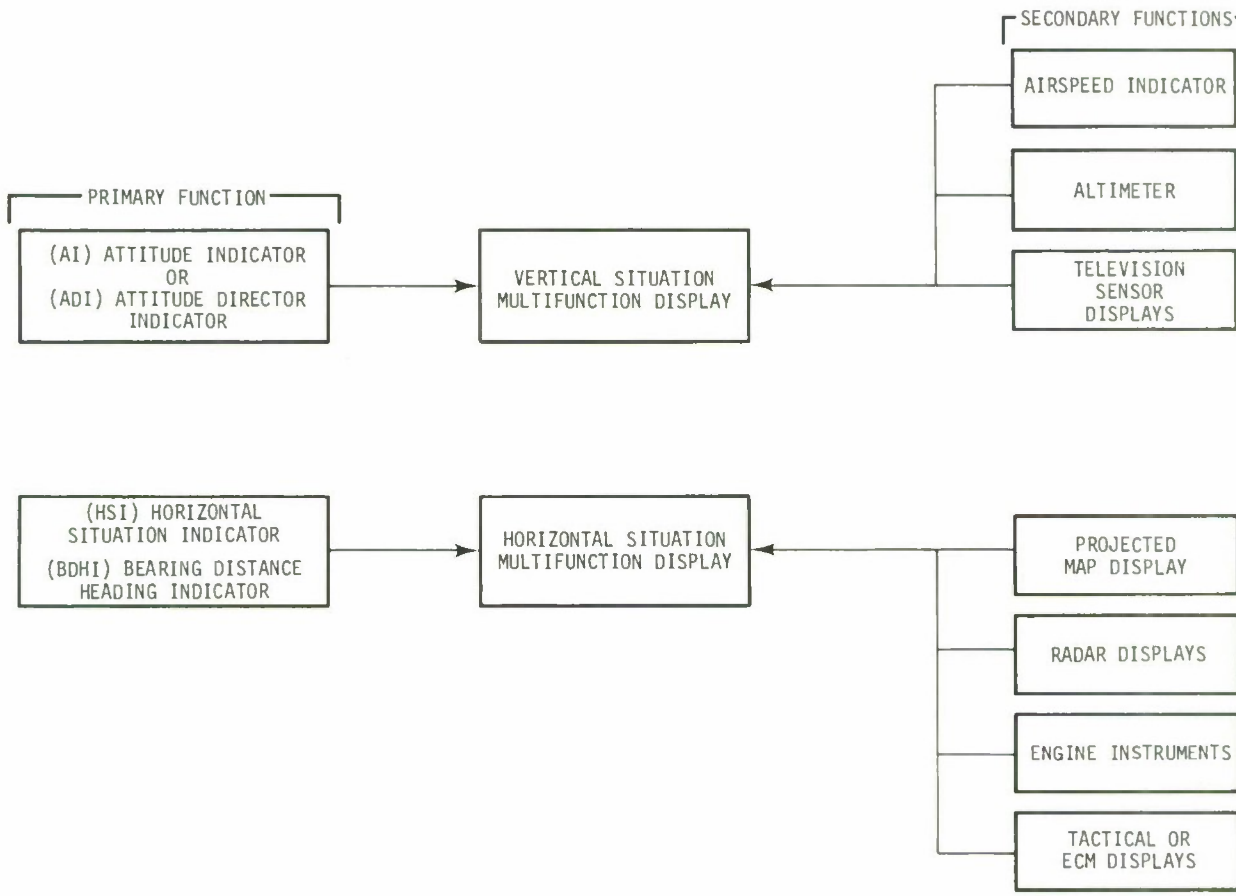


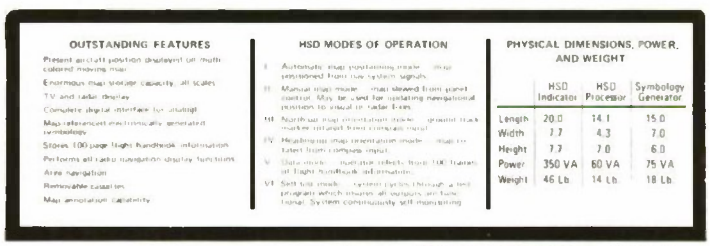
Figure 3. Horizontal and vertical planes; primary and secondary function.

the processing of data from the aircraft sensors, and the control-communication logic. Therefore, the main components of the display management computer are (1) input/output conversion electronics, (2) central processor, (3) main memory, and (4) symbology generator. The main memory size is between eight and sixteen thousand words. To augment the memory storage capability, a fifth electronic box, an auxiliary data storage, is used. This unit is a magnetic tape memory with a storage capability of 15 million bits. The auxiliary data storage is used for fixed format data such as CRT map overlay, graphical formats, alphanumeric data, and any other fixed data information.

In conclusion, the need for multifunction displays has been shown by their use in advanced aircraft with complex and demanding missions. The workload of the pilot is reduced by the integrated display of flight parameters and sensor outputs, and the reduction of controls. However, if the multifunction display is not used in an overall display system concept covering the vertical, horizontal, and operator-display communication plane, there is a potential problem that its use may increase rather than decrease the pilot's workload since the multifunction display would be just another instrument among many that is to be managed. The "I" concept presented here is a set of multifunction displays that provides the operator with a total integrated display of all three dimensional planes.

The CRT head-up display (HUD) can replace the vertical situation multifunction display. However, the HUD is limited in displaying television sensor outputs, since it can display them only under certain restrictions due to visibility difficulties under high ambient light conditions. This paper treats the head-down displays, the displays mounted in the instrument viewing plane.

Figure 4. Combined CRT/projected map display.



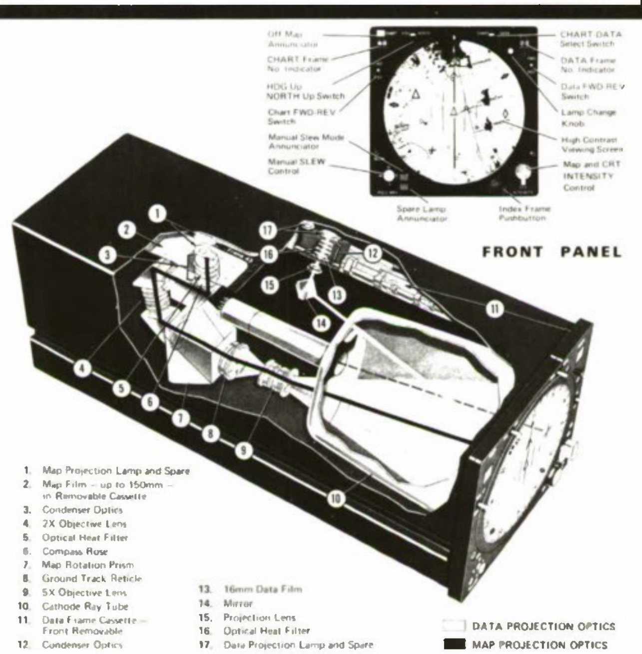
OUTSTANDING FEATURES

- Present aircraft position displayed on multi colored moving map
- Enormous map storage capacity, all scales
- TV and radar display
- Map referenced electronically generated symbology
- Stores 100 page flight handbook information
- Performs all radio navigation display functions
- Area navigation
- Removable cassettes
- Map annotation capability

HSD MODES OF OPERATION

PHYSICAL DIMENSIONS, POWER, AND WEIGHT

	HSD Indicator	HSD Processor	Symbology Generator
Length	20.0	14.1	15.0
Width	7.7	4.3	7.0
Height	7.7	7.0	6.0
Power	350 VA	60 VA	75 VA
Weight	46 Lb	14 Lb	18 Lb



1. Map Projection Lamp and Spare
2. Map Film – up to 150mm – in Removable Cassette
3. Condenser Optics
4. 2X Objective Lens
5. Optical Heat Filter
6. Compass Rose
7. Map Rotation Prism
8. Ground Track Reticle
9. 5X Objective Lens
10. Cathode Ray Tube
11. Data Frame Cassette – Front Removable
12. Condenser Optics
13. 16mm Data Film
14. Mirror
15. Projection Lens
16. Optical Heat Filter
17. Data Projection Lamp and Spare

Figure 5. Combined CRT/projected map display--F-111.

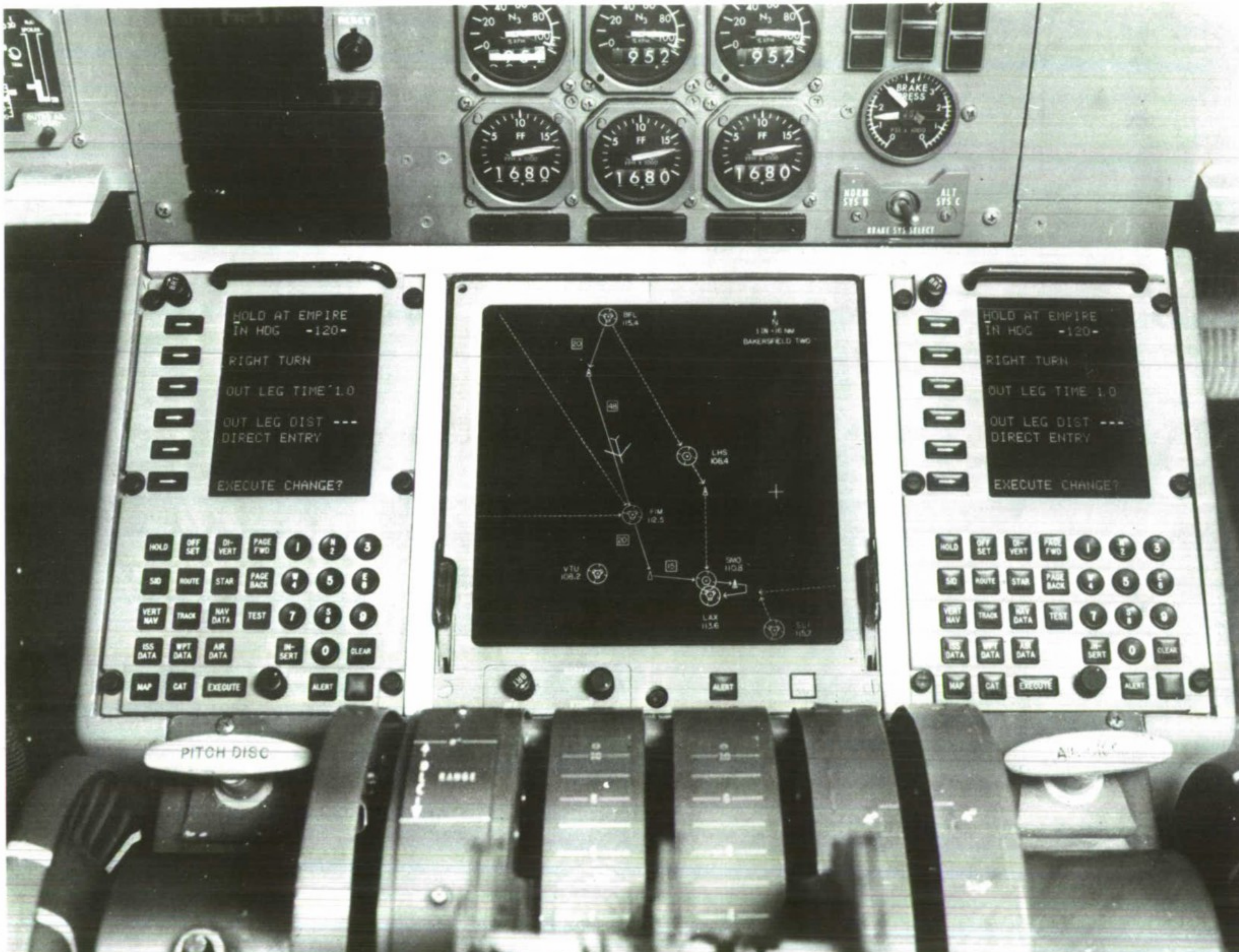


Figure 6. R-navigation displays--L-1011 installation.

Figure 7. Electronic horizontal situation indicator.

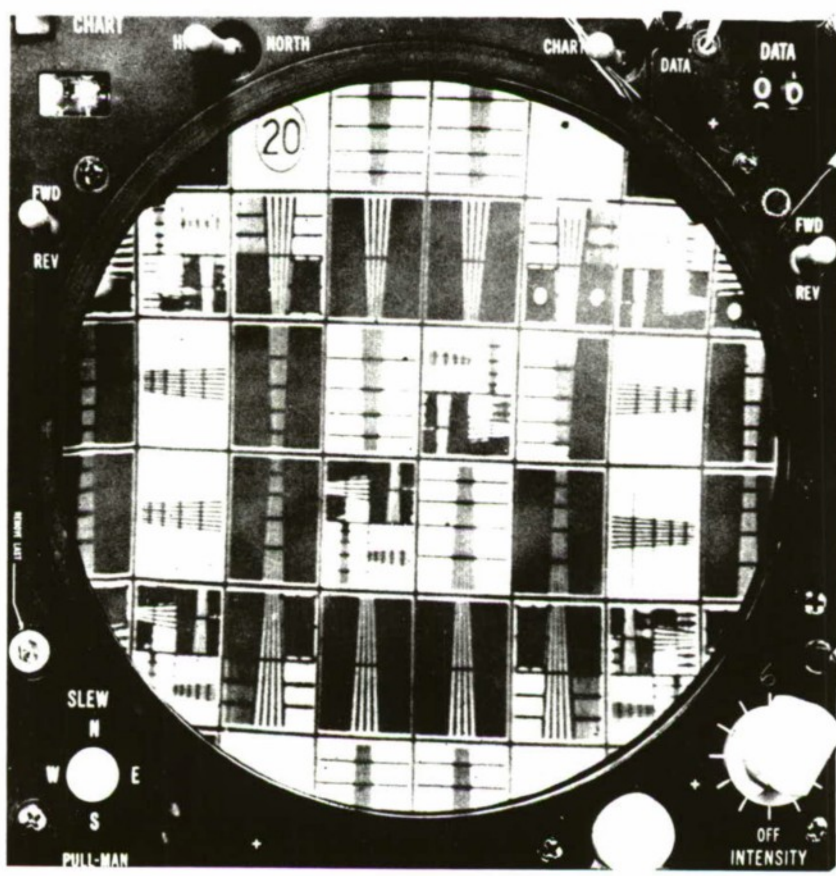


Figure 8. Horizontal situation display low light level TV resolutions and shades of gray.

TACTILE INFORMATION PRESENTATION (TIP)

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Abstract: *For years researchers have been trying to develop ways to present essential information to a pilot without increasing the information load on the already overworked audio and visual channels. Although many people have considered using tactile warning as a possible solution, embodiments of the tactile device have been too encumbering or the tactile signal too unpleasant for practical use.*

This paper describes TIP (Tactile Information Presentation), which is a device that produces a distinct tactile stimulus by inducing a high-pressure pulse of air into the pilot's anti-g suit. A special circuit designed to sense a preset voltage from either the angle-of-attack transmitter or an accelerometer triggers an oscillating circuit which induces a high-pressure pulse of air through a bypass in the standard anti-g valve and into the pilot's g-suit.

Experimental testing on the Aerospace Medical Research Laboratory's centrifuge has shown three cycles per second to be the most distinct pulse frequency. Although g-limit information could also be presented, the most useful information seems to be an angle-of-attack signal which can be used to indicate maximum maneuvering alpha. Since a useful signal is obtained even when the g-suit is not inflated, landing angle of attack may also be presented which is of interest to the Navy with its special information requirements for carrier landings.

This paper gives a physical description of the TIP devices, centrifuge test results, and the results of Air Force flight tests currently being conducted on F-4s and an F-100. Possible future improvements and developments are also discussed.

INTRODUCTION

Today's modern fighter aircraft have become so sophisticated and complex that the pilot is placed under great demands to process all the available information and perform all the required flight tasks. As more and varied types of avionics equipment are added to fighters, so the number of warning lights and aural tones increases. In recent years, researchers have tried to develop new ways to present essential information to a pilot without increasing the information load on the already overworked audio and visual channels. Although many people have considered using tactile warning as a possible solution, embodiments of the tactile device have been too encumbering or the tactile signal too unpleasant for practical use. TIP (Tactile Information Presentation) is a new way of providing a distinct tactile stimulus by inducing a high-pressure pulse of air into the pilot's anti-g suit. Since the anti-g suit is already worn by most fighter pilots, the use of TIP provides no further encumbrance for the pilot.

A tactile warning, which avoids the overworked audio and visual channels, can be used to present maneuvering angle of attack, landing angle of attack, g-limit, or energy management information. A tactile signal could provide warning when a preset optimum or maximum maneuvering alpha is reached without requiring the pilot to bring his eye scan into the cockpit to monitor his angle-of-attack meter. Such a signal could be particularly valuable in air-to-air combat where a pilot visually "locks-on" to his target which is often above or even somewhat behind him and tries to force the enemy down in front of him within gun range. Since a useful signal is obtained even when the g-suit is not inflated, landing angle of attack may also be presented, which is of special interest to the Navy with its precise angle-of-attack requirements for carrier landings. TIP may also be used to provide g-limit information eliminating the requirement for the pilot to shift his eyes to the g-meter when outside vigilance is critical. Such a tactile warning could signal a pilot when he has reached a predetermined g-limit--either a g-limit for his ordinance or aircraft or a maneuvering threshold for training. The tactile signal may be tied to any system that can produce a voltage change with a change in status. Another possible embodiment would use the tactile signal to warn of changes in energy management (Q-TIP) as processed by the aircraft's central air data computer.

PHYSICAL DESCRIPTION OF TIP

If a normally closed solenoid valve is included in a bypass circuit built around a standard anti-g valve, it is possible to impart a high-pressure pulse of air into the pilot's anti-g suit by opening and closing the solenoid valve. The rate at which the solenoid is actuated and released determines the frequency of the signal, which is a major variable in supplying information to the pilot. Since the solenoid is normally closed when the unit is not giving a pulse signal, the bypass circuit is totally blocked off, and the path for air through the anti-g valve to the anti-g suit functions as it presently exists in fighter aircraft. In addition to the bypass circuit, the other major component of the system is a sensing box (Figures 1 and 2) which compares a voltage from an accelerometer (G-TIP) or the angle-of-attack transmitter (alpha-TIP). The pilot selects a threshold level of angle of attack or g by dialing a knob (potentiometer) on the control box. When the preset threshold is reached, the voltage from the angle-of-attack transmitter or the accelerometer will exceed the reference voltage the pilot previously dialed in. The two voltages are compared in the sensing box and when the preset reference level is exceeded, an oscillating circuit is activated which opens and closes the solenoid at a preset frequency. The frequency of the pulse can be easily changed by setting a knob on the sensing box which changes the value of a potentiometer in the oscillating circuit.

A pressure regulator is included in the bypass circuit to bleed off any air pressure greater than 150 psi. By using a three-way free venting normally closed valve with an average exhaust Cv factor of 0.046, it is possible to produce a flow rate of four standard cubic feet per minute through the solenoid.

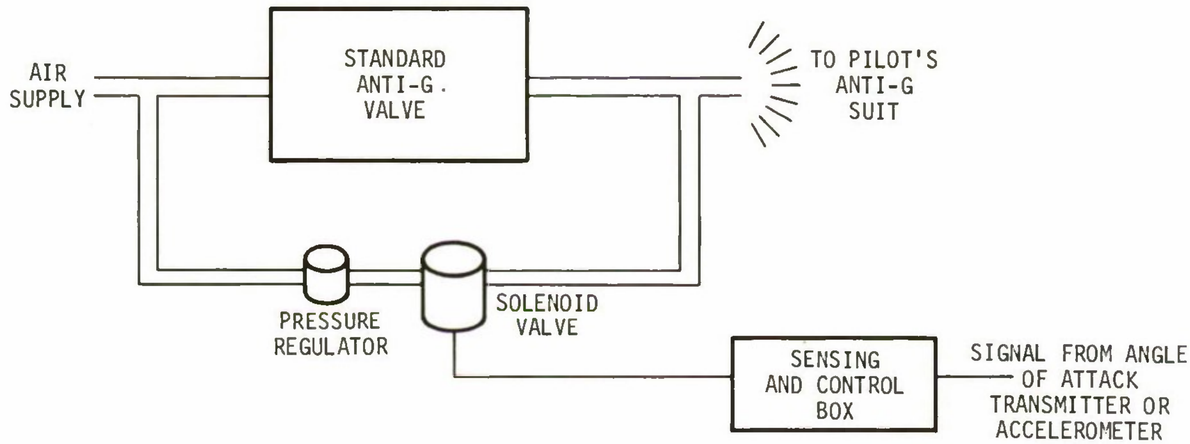

Figure 1. Schematic of the Tactile Information Presentation (TIP) device.

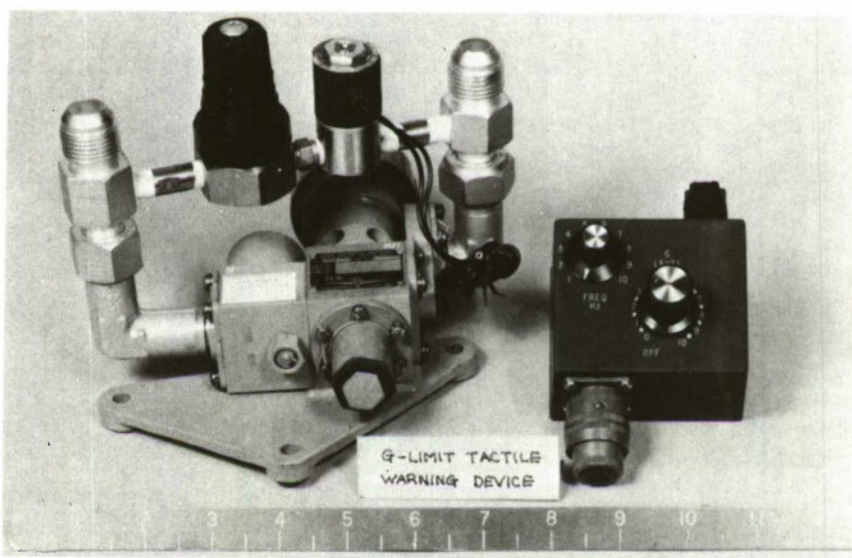

Figure 2. A close-up photo of the components of g-tip.

The F-4 aircraft at 100% military power has a pressure in the airlines to the anti-g valve of 265 psi. By reducing this pressure to a maximum of 150 psi by placing a pressure regulator in front of the solenoid, it is possible to use a smaller, less bulky solenoid and still have a large enough flow rate to produce a distinct stimulus. With smaller, less bulky solenoid valves the average exhaust Cv factor tends to get smaller as the maximum operating pressure differential rises. Thus, according to the formula,

$$\text{Flow rate} = 22.7\ \text{Cv}\ \frac{(\text{Pd})\ (\text{Ip})}{\sqrt{(460^\circ + {}^\circ\text{F})\ (\text{Sg})}}$$

where Flow rate = standard cubic feet per minute
Cv = flow coefficient
Pd = pressure drop
Ip = inlet pressure
Sg = specific gravity

there is a tradeoff between higher pressures and correspondingly lower Cv to produce the largest flow rate and still have a solenoid of a reasonable size and weight. By selecting a pressure of 150 psi, the corresponding Cv for the valve is 0.046 and the largest flow rate is produced.

DETERMINATION OF OPTIMUM FREQUENCY

Determination of the optimum frequency range of the tactile pulse was partially guided by an attempt to avoid the frequencies near the more commonly produced aircraft buffet frequencies which often occur around 20-30 Hertz. Through a series of bench tests, it was decided that frequencies above 8 to 10 Hz. were too fast and tended to be damped out. A frequency range between one to five Hertz seemed reasonable and in June 1971 an experiment was conducted at the Aerospace Medical Research Laboratory on the Dynamic Environmental Simulator (DES) centrifuge to determine the optimum frequency of the pulse signal. A two-factor, repeated-measures design was employed. The two factors involved were g-level and tactile pulse frequency. The six subjects who participated in the experiment received a signal randomly at either the 2g, 5g, or 6.5g level for each of three possible pulse frequencies, 4 Hz., 2.5 Hz., or 1.5 Hz. At each of these three frequencies, one run up to 7g's with no signal was included to preclude subjects anticipating a signal on each trial. Each subject made 12 runs on the centrifuge, receiving each pulse frequency at each g-level (or no signal) in a completely randomized sequence. Each centrifuge trial was a ramping function peaking about a half a g higher than the predetermined g-warning level. Each trial lasted less than a minute with the subject receiving the tactile stimulus just before the peak g-level for that run.

Subjects performed a secondary task, a tracking chase using F-15 dynamics on a display located in front of them in the centrifuge cab. The tracking task further insured against anticipation of the tactile signal.

When the subject felt the tactile signal, his response was to pull a trigger located on his control stick. The time the pulse was activated and the time the trigger was pulled were recorded on a Brush recorder so the reaction time for each pulse frequency could be determined. After receiving each signal, subjects expressed their opinion of the signal with regard to its discriminability in comparison to previously received signals. These subject opinions were tape recorded for each trial so they could be played back later for analysis.

The most important result of the experiment was that not one warning signal at any frequency was missed by any subject. One subject who blacked out near 6g's even reported that he felt the tactile signal at the 6.5g-level after blacking out. No subject reported feeling a signal on a trial when no signal was given.

Pulse frequency turned out to be less critical than originally expected. All the frequencies were pronounced and could be distinctly felt at all g-levels. However, subjects tended to react more slowly to the 1.5 Hz. frequency because they had to wait an instant longer to get the rhythmic pulse they knew to be a signal. At lower g-levels when the anti-g suit was less inflated, the 1.5 Hz. "thump-thump" was more distinctive than the other frequencies, even though it produced slightly longer reaction times. Conversely, the four Hertz rate produced a "boom-boom-boom" which was more distinctive at the higher g-levels when the suit was more inflated. Over all g-levels, subjects agreed that the 2.5 Hz. frequency was the most distinctive and pronounced. The signal was strong enough so that no subject missed a given signal, yet no subject reported the signal as uncomfortable.

No performance degradation of the anti-g valve or suit was recorded while testing the tactile warning system. Anti-g suit pressure was constantly monitored and recorded through each trial, and the introduction of the pulse signal had no adverse effect on the suit pressure. In fact, a very slight increase in suit-fill rate was noticed in some cases which would be advantageous to a pilot under g-loading. The suit-fill rate curves were the same as for a standard g-protection system with a ripple on top of the normal fill rate line when a pulsing signal was given. Since the standard anti-g valve automatically vents any additional suit pressure above 11 psi, there is no safety hazard to the pilot. An advantage of TIP is that a redesigned anti-g valve to include the TIP bypass circuit would

be comparable to all the presently used anti-g suits, hoses, and other auxiliary g-protection apparatus.

FLIGHT TEST

After receiving acceptance of the concept by subjects in the centrifuge experiment and determining the whole frequency range between one and four Hertz was useful with an optimum frequency of about 2.5 Hz., the next step was to evaluate TIP's effectiveness in an actual airborne environment and to obtain pilots' subjective opinions of the concept. Accordingly, two F-4Cs of the 4950th Test Wing, Wright-Patterson AFB, Ohio, were equipped with TIP--one with alpha TIP and one with g-TIP. Since the F-4 under g-loading has a great deal of buffet, an F-100 was also equipped with g-TIP to examine the utility of g-TIP on an aircraft less susceptible to strong buffet.

In Figures 3 and 4, the installation of the g-TIP in the F-4C, it can be seen that the anti-g valve and bypass circuit are installed in almost the same place as the anti-g valve on an unmodified F-4C. The sensory/control box has been attached to Flight Station 120 above the pilot's left inboard panel by a bracket; the box includes a knob to adjust the pulse frequency between one and five Hertz in addition to a knob for presetting the TIP alpha or g threshold. Of course, since these items are prototype equipment, they are bulky and do not fit neatly into the cockpit. A final version of TIP would incorporate the bypass circuit into a redesigned anti-g valve probably no larger than the present valve and place the sensory/control box knobs flush with the instrument panel. Thus, the weight, space, and cost requirements of the device are minimal.

The flight test profile allowed the pilot freedom to use TIP to signal him of performance thresholds in whatever way was most valuable to him. Since the device was flight tested concurrently with other projects, the pilots often used g-TIP to signal them if they were pulling too many g's for test equipment used in some other project on the aircraft.

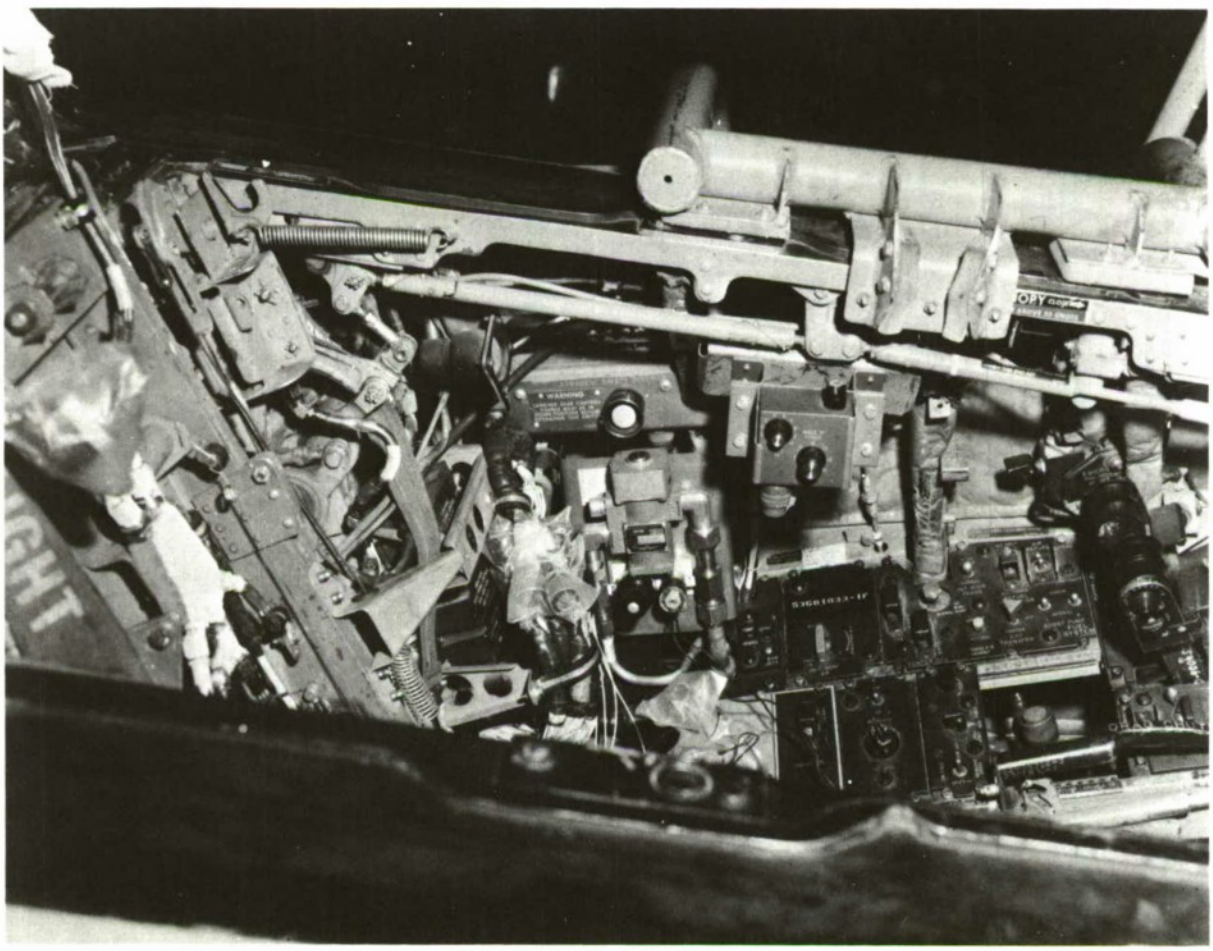

Figure 3. A view of the F-4 cockpit showing installation of the alpha TIP (Angle of Attack Tactile Information Presentation).

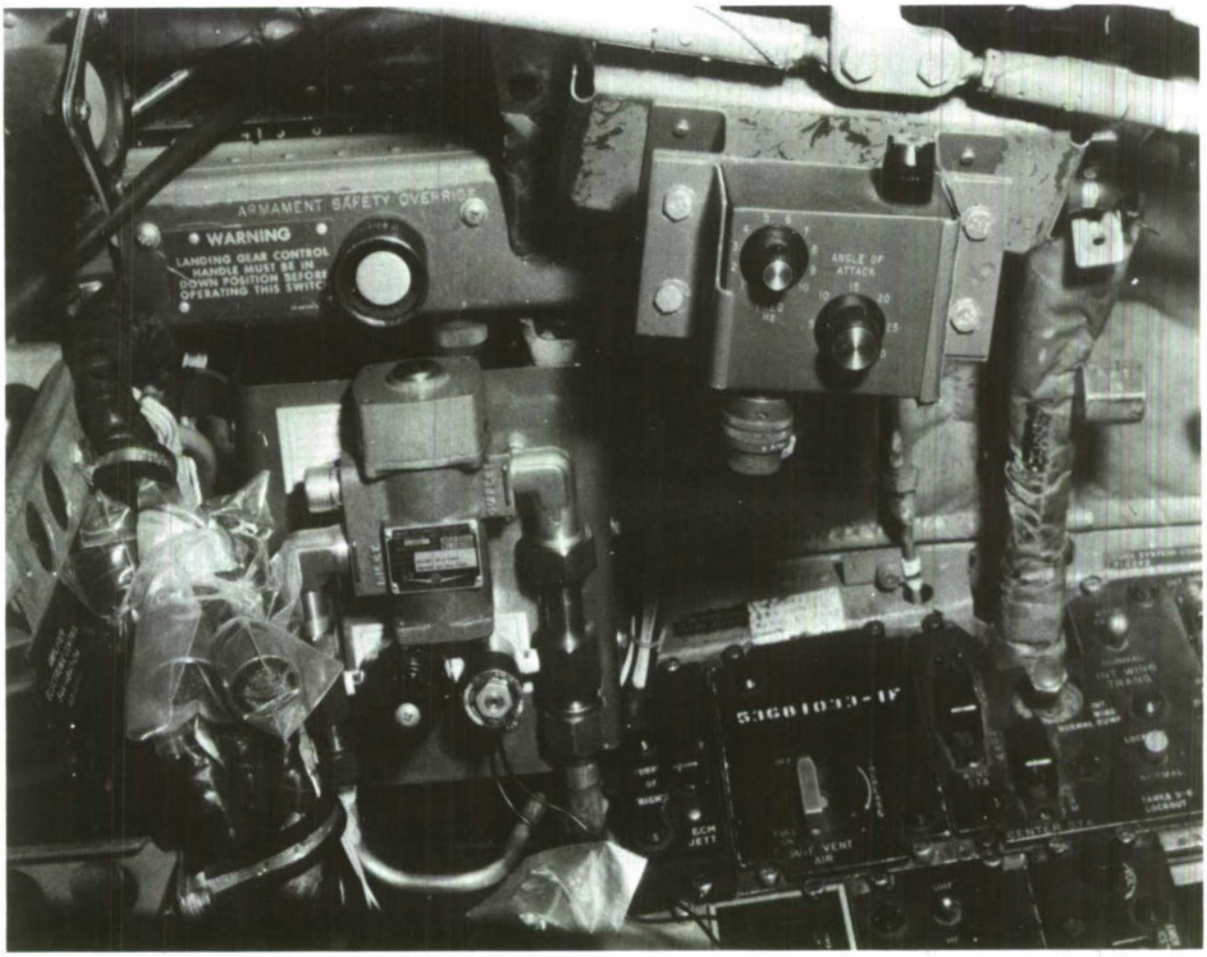

Figure 4. A close-up of the alpha TIP installation in the F-4.

Specific items in the alpha TIP flight test profile include maneuvers in which optimum or desired angle of attach was critical and landing approaches using TIP angle-of-attack information. The flight test profile for g-TIP included several simulated pullouts from an air-to-ground bombing/strafing maneuver in which several different ordinance limitations were assumed and several turns or other maneuvers at different g-levels for which g-loading information was valuable.

At the conclusion of each flight the pilot completed a short questionnaire which was designed to measure his overall opinion of the concept, his opinion of the strength of the tactile signal, his opinion as to any discomfort associated with it, and his opinion of the optimum pulse frequency.

SPECIFIC RESULTS FROM THE FLIGHT TEST

From the evaluation of the pilot questionnaire and from talking to the pilots, some specific problems were identified and some possible areas for future development were suggested. Overall, pilot opinion of the concept was favorable although specific pilots thought the signal should be tied to alpha rather than g or vice versa. The pilots found the signal to be pronounced and distinct without being uncomfortable except in the case of the g-TIP on the F-4C. When the F-4 was producing a great deal of heavy buffet, the g-TIP signal tended to be masked and was hard to distinguish. For applications of the device that require signaling the pilot in high buffet regimes on certain aircraft like the F-4, it may be necessary to increase the intensity of the signal. It may be possible to insert a flexible tube across the abdomen which pulsates between the body and the g-suit to produce a stronger pulse. With such a flexible tube it would be possible to localize the signal and present more or different types of information. If two tubes, one running down each leg, were used, perhaps more than one type of information could be given depending upon how well a pilot could learn to discriminate between the two localized signals.

The pilots generally agreed that a pulse frequency of three to four Hertz was the most discriminable. One pilot had used the angle-of-attack signal for landing and found it was very helpful. The Navy has been provided with alpha TIP equipment and is scheduling flight tests at Patuxent River Naval Air Station through the Naval Air Test Center. The Navy's flight test will primarily involve testing the utility of alpha TIP on landing but will also evaluate its value in providing maneuvering alpha information.

FUTURE DEVELOPMENTS

Through pilot comment, several possible areas of future development were suggested. One possible development would be to provide angle-of-attack trend information in addition to just threshold information. By providing "zero beating" it is possible to allow a band or tolerance of say ± one unit around a preselected angle of attack. If the aircraft is low, the pilot would receive a TIP signal of low frequency and increasing intensity, or of low frequency which would get lower as he got further below the optimum alpha. If the pilot is above the selected alpha, the pulse would be of high frequency and get stronger or increase in frequency as the airplane went further above the optimum alpha. With this system the pilot would not only know whether he was above or below the threshold value, but also how far above or below the value he was.

In the future, there will be further development of the TIP concept and further refinements. However, even in its present stage of development, TIP is a valuable means of providing essential flight information to a pilot through a previously unused information channel which avoids further burdening the already overworked audio and visual senses.

ACKNOWLEDGMENTS

The original idea for the Tactile Information Presentation concept came from Lt. Col. Richard L. Ravenelle who submitted the idea as Aeronautical Systems Division Suggestion No. 71-161. A specific embodiment of the idea was developed by Capt. David E. Thorburn. Capt. John Lyons was helpful in providing engineering improvements, and Capt. Dana B. Rogers supplied valuable assistance in preparing and conducting the centrifuge test of TIP.

FUNCTION INTERLACE MODIFICATIONS TO ANALYTIC WORKLOAD PREDICTION

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HONEYWELL, INC.

Abstract: *Analytic prediction of operator workload has been used to evaluate the result of allocating functions to human operators for a specific system concept. A common workload definition used is the ratio of time needed to perform all required tasks to the time available. This technique has proved useful in that system concepts which impose excessive workload demands on the operator can be abandoned early in the development cycle.*

The usual techniques involve task analysis, with performance time prediction based on eye-movement data, information processing time data and time and motion data. The human is typically modeled as a single-channel device. The results are quite conservative if complex well-practiced tasks are involved. Function interlace provides a model which permits time-sharing of attention capacity to yield workload predictions more closely in agreement with simulation workload data. The theory is not as yet substantially developed, although some validating laboratory measurements have been made.

PURPOSE OF ANALYTIC WORKLOAD PREDICTION

To date, no generally applicable deterministic method to formulate system concepts has been advanced. Typically, complex system concepts are developed by seat-of-the-pants methods which depend heavily on expertise for their successful formulation. It is frequently the case that the allocation of functions to man or machine is dependent largely on tradition, and a knowledge of what basic capabilities of the human operator apply in performance of a given function. Until the advent of such a deterministic method, or methods, we must continue to rely on the post hoc evaluation of a formulated system concept.

Workload, as used in this paper, is a measure which is related to the amount of time required to perform the total of all tasks imposed on the human operator by reason of a specific functional allocation. Workload is the ratio of the required performance time to the time available within the time constraints regulated by a mission. Further, we make the tacit assumption that, when converted to percent, 100 percent is the upper useful limit of human capacity. Hence, when a particular allocation of functions to a human operator results in one or more segments of time in which workload values greater than 100 percent are predicted, the human operator is said to be overloaded, and the system concept is reconsidered with a workload reducing modification to be made.

The technique involved in system concept formulation, evaluation, and eventual selection and design of equipment to satisfy some specified set of operational requirements is outlined in schematic form in Figure 1. The techniques are necessarily iterative, in that any problems identified throughout the process force attention backward to modify some portion of the concept. Briefly, the methodology is one of specifying a concept, allocating functions, evaluating the individual pieces to predict their adequacy of performance, and finally evaluating the total system by evaluating operator workload. The choice of workload is due in large part to the lack of evaluation metrics which describe total man-machine performance. In complex systems, probability of successful performance of a large number of functions often becomes a prohibitive evaluation to make. One quantitative estimate of human performance is workload--and a strong relationship can be demonstrated between workload levels and human reliability. Because of the relative simplicity of workload prediction, therefore, its utility early in the development cycle is the reason for its interest to us.

Workload prediction, as we use it, is the last step in the analytic process. Only those functions that can be performed to or above criterion levels as specified by the operational requirements of the system are analyzed through the workload evaluation. We would expect therefore, that the measured workload--in a simulator for example--would be different because the human operator could choose to perform above criterion performance level, yielding thereby a higher workload score than predicted. (Also the reverse is true, but we avoid it. The human operator can perform at below criterion levels, with a consequently lower workload. We penalize the subject in the laboratory for this mode of

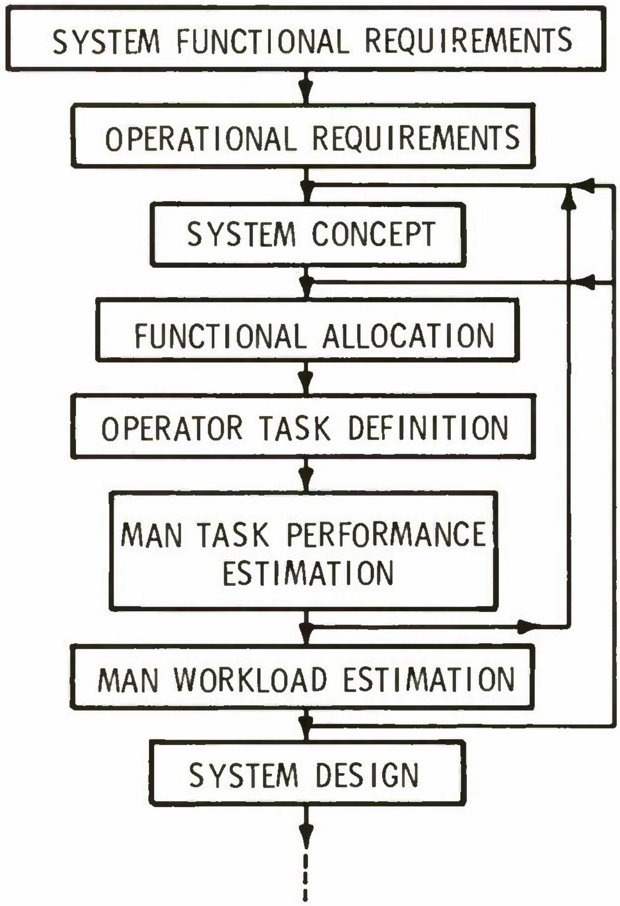

Figure 1. Steps in system concept formulation and evaluation.

operation.) Since we seek a performance index for the total system concept, this error is acceptable. What is of prime interest is that some margin of human capacity beyond that required to just barely operate the system at minimum be available for contingencies, etc. At this point in the use of workload methodology to predict man-machine system capability, we have minimal data as to the relationship to the "real world."

THE PROBLEM

Workload has been predicted in many ways and for many years. Our own experience with workload prediction goes back a dozen years or so. The problem which has been encountered frequently is one of extreme conservatism inherent in the traditionally arrived at workload characteristics.

Functions allocated as the responsibility of human operators can be described as requiring one of two possible modes of behavior. One is commonly called the "discontinuous task." This is essentially a discrete task, one involving the detection and identification of a stimulus, the formation of a decision, and (sometimes) the actuation of a discrete switch or a series of such switches. Industrial engineers/psychologists have studied this case extensively, and a good data base is available. By use of this data base, very good predictions of workload for the average, the below average, and the skilled operator can be made. This prediction has been validated sufficiently to be very useful to us.

The problem comes about when the other mode of behavior is demanded by a function. This is the "continuous task." Actually, the truly continuous task has been studied in considerable detail. The tracking study literature is extensive enough to keep one reading for a long time. Also, workload at a truly continuous task is 100 percent by definition. What causes a problem is the combination of these two types of tasks within the same period of time. The multiple functions must therefore be time-shared somehow by the individual in order to maintain proper

operation of the total man-machine system.

A case in point--and the one that first utilized a function interlace theory--was an avionics study for a helicopter (Lindquist, 1971). Some of these functions were flight control, navigation, communication, search systems monitoring, and surveillance. The object was to determine the minimum avionics set that would permit adequate mission performance, assure flight safety, and minimize pilot training requirements. The initial workload prediction techniques resulted in an obvious overdesign--in that workload levels from the analysis were much higher than those intuitively known to exist in actual flights of a type similar to those being proposed.

The traditional assumption of the human operator as a single-channel device resulted in overly conservative workload estimates. It was known that skilled pilots were somehow able to manage more efficiently than the single channel model would permit. Laboratory part-task simulation, however, corroborated quite well with the workload values used in the analysis. The obvious conclusion, therefore, was that a more efficient time-share model was needed to represent the skilled pilot in this situation. Such a model was developed, therefore, and used to modify the summation of individual task workloads such that the total workload time function was less than the arithmetic sum of the individual contributors.

TECHNIQUE OF WORKLOAD PREDICTION

The statement was made earlier that workload prediction was relatively simple to perform. This statement is true if we have a reasonable data base from which to proceed. It can be extremely laborious, time-consuming and open to questions of validity if we do not have this data base handy. In the following paragraphs, I will briefly mention some techniques that have proved useful in predicting the workload of individual functions. This discussion will then lead to the function interlace technique for arriving at the workload sum.

The old standby task analysis is a useful method for evaluating the time required to perform the discontinuous tasks involved in operating a complex system (Siegel & Wolf, 1961). The task analysis technique handles discrete sequential operations quite well. Performance time is estimated as:

- Transition time (short, and constant).
- Monitoring or reading time, proportional to information content in the stimulus.
- Decision time, proportional to number of choices in the control.
- Reach and control actuation time, if an action is required.

These estimates have been well enough documented in the literature to make it unnecessary to expound further. The principal hypothesis is that performance time can be best estimated by separating performance into sensory and motor components (Burns & Burdick, 1961). Then operator channel capacity and display-control coding together determine the processing rate, and therefore the time required to make the response decision.

In the flight control function analysis, as in most continuous tasks, a different technique is required. It is established by a number of studies that pilots set up a relatively inflexible scan pattern, which consistently scans instruments at different rates, and for different durations of time (Senders, 1966). A useful workload estimate is obtained by a modeling of the visual distribution of attention. This model postulates that attention is distributed according to the bandwidth of the signals presented on each of the instruments and that the interobservation interval is a function of the previous value read. This requires, of course, that an estimate be made of the frequency characteristics of each of the information signals of interest. Our experience has been that an unknown vehicle handling quality description makes this model difficult to apply. Hence, instead of solving the differential equations to obtain the frequency descriptions, we have gone to the part-task simulation.

Having a simulation facility available, our choice frequently has been to obtain man-in-the-loop simulation data on workload by the concomitant task method. The technique here has been to add a secondary task whose workload has been easy to measure. The subjects are either required to satisfy the secondary task, and the performance decrement with levels of force-paced workload obtained, or a given performance criterion is maintained and the subjects work at a self-paced secondary task. In either technique, an estimate of primary task workload is obtained.

TECHNIQUE OF FUNCTION INTERLACE

In one way or another, an estimate is obtained of workload as a function of time for all the individual functions of the system concept being evaluated. Then the total workload sums are obtained by a summation process:

W1 = instantaneous workload predicted for function 1

W2 = instantaneous workload predicted for function 2

$$\Sigma W = W1 + W2 - I \times W2$$

Where the coefficient I is the interlace coefficient typical for the combination of the two functions under consideration.

The combining coefficients were determined by two methods--one by analysis and the other by simulation studies which used, in each case, a tertiary workload task designed for maximum interference with the other two tasks. A problem exists here, of course. How do you measure a hypothesis of interlace effects independently of interlace effects?

The term "function interlace" was coined to describe the phenomenon most easily understood as the apparent ability of skilled operators to perform tasks simultaneously. That this is limited to skilled operators performing practiced behavior is well known. It may be that this is the difference between the student pilot who is too busy to control his aircraft and the skilled pilot who flies it, reads maps, munches lunch, etc. Function interlace may in reality stem from our inability to model man's behavior at as molecular a level as we must to account for his capability.

The hypothesis taken is that the traditional single-channel model of the human is too simple and constrictive. Some parallel performance of subtask activities was assumed, and based on these, a set of rules was developed to combine individual task workloads. A literature search revealed no direct basis for this. One investigator (Noble, 1968) did anticipate that training might produce SOR elements into coordinated spatiotemporal patterns of receptor-effector activity, which I interpret as a task interlace skill. A practical approach (Gabriel, 1968) trained pilots deliberately to interlace intra- and extra-cockpit data gathering. Smith and Patz (1970) state that steering and tracking are two separate definable modes of response, but since these are practiced together operationally, they may be a prime case of task interlacing.

Figure 2 presents a possible schematic model for interlace. The input information is obtained from a number of sources, only a few of which (instruments) we attempt to handle in the model. Short-term memory then operates in a manner that presents complex coded information to the cognitive processes at a very rapid rate, and when needed. Following decision formulation, complex motor commands are

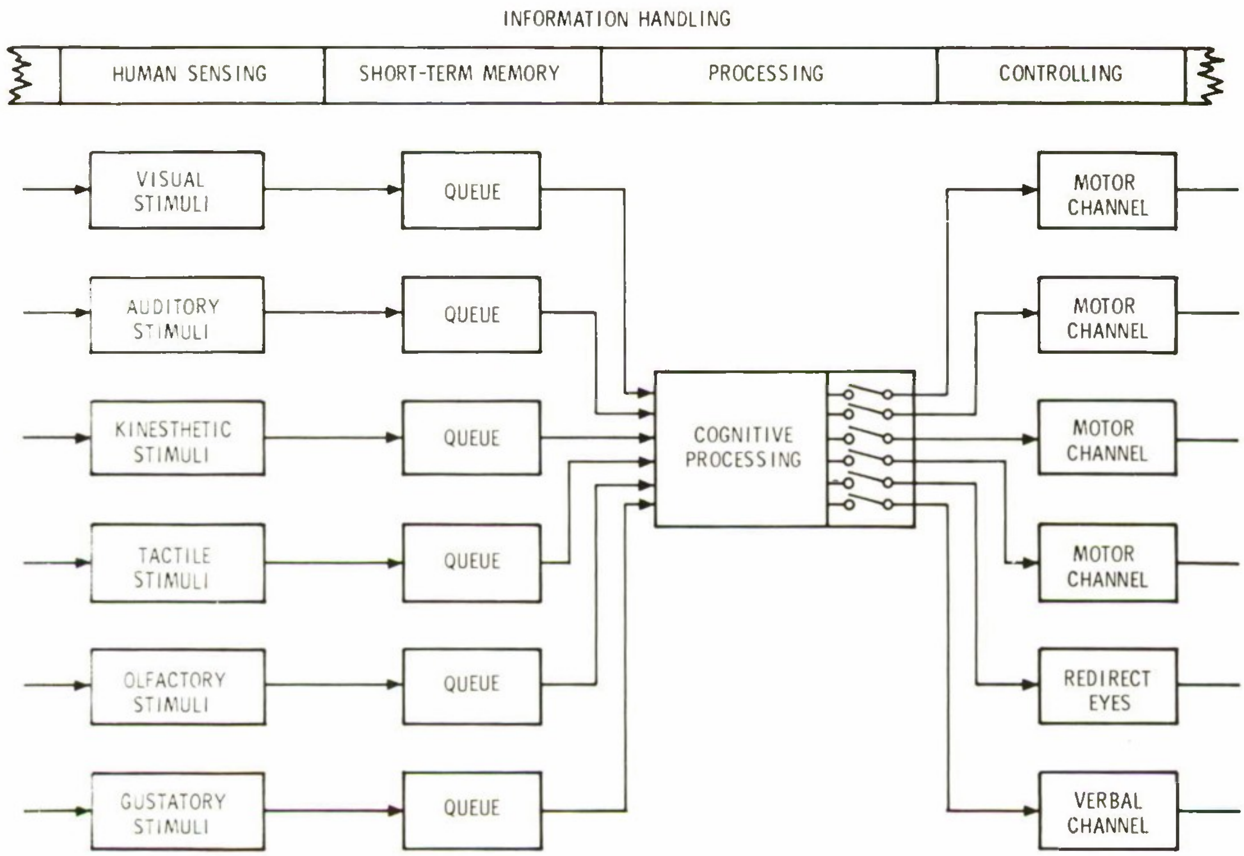

Figure 2. Queueing model analog of function interlace.

formulated and relayed onward. The hypothesis is that where no direct incompatabilities exist, the sensing behavior can be considered a parallel operation. Cognitive processing was modeled as a serial operation. The single-channel model was preserved here. Motor channels were also allowed to be parallel in operation, again assuming no competition for the limb under consideration.

A very practical condition that must be satisfied, besides the obvious competitive one, is the degree of uncertainty that exists in the various candidates for interlace. We know that when conscious mental activity is being performed, as opposed to well practiced motor skills, attention to visual and auditory simulations of a symbolic sort must be carried out simultaneously, then only one sensory input is typically utilized. The information in the other appears to be lost, or at least performance is degraded to a considerable degree. To estimate how symbolic or how well practiced the performance of the task combination may be requires considerable attention to the unique characteristics of each and every combination in which the combination arises. Hence, considerable judgment of a conservative nature has been used to date. If a situation appears to be less than a very habitually encountered one, or elements of a situation are at all uncertain according to judgment, then we typically rejected interlace, or severely curtailed our estimates of the extent of the interlace effect.

The model was developed by first cataloging each function into its input sensory modality (the major one) and the output motor channel. Then an interlace table was prepared for the common combinations (see Figure 3). These combinations were then worked out analytically using scan and dwell models, information processing time predictions, and methods time measurement data to determine individual activity times. The final combinations were made using the summation rules--parallel sensory inputs and outputs, serial information processing where these applied, parallel sensing, but the remainder serial, where these applied, etc. The results are tabulated in Figure 3.

However, this does not predict the interlace effects on the function level. To do this meant determining what proportion of the pairs worked out above applied to a particular function and which required some estimates of task activities. Eye-motion data was used in part to make these particular judgments. The results are tabulated in Figure 4.

A series of simulation studies was now performed to attempt to measure the actual coefficients. A fixed-base helicopter simulation was used, and tasks were designed to simulate the various function pairs to be interlaced. Pilot subjects were used, and pretrial training to performance plateaus was carried out. The results are tabulated in

	VISUAL - MOTOR	VISUAL - VOCAL	VISUAL - NO	AUDITORY - VOCAL	AUDITORY - MOTOR	AUDITORY - NO	KINESTHETIC - MOTOR	KINESTHETIC - VOCAL	KINESTHETIC - NO
VISUAL INPUT MOTOR OUTPUT	10	20	20	80	40	90	50	70	90
VISUAL INPUT VOCAL OUTPUT		10	20	40	70	80	60	60	90
VISUAL INPUT NO OUTPUT			20	80	80	90	70	80	90
AUDITORY INPUT VOCAL OUTPUT				00	30	50	50	70	80
AUDITORY INPUT MOTOR OUTPUT					10	60	60	80	80
AUDITORY INPUT NO OUTPUT						20	70	90	80
KINESTHETIC INPUT MOTOR							00	30	10
KINESTHETIC INPUT VOCAL								00	10
KINESTHETIC INPUT NO OUTPUT									0

Figure 3. Percentage interlace estimates according to task activities.

	SYSTEMS MONITORING	COMMUNICATION	SURVEILLANCE	SEARCH	NAVIGATION
FLIGHT CONTROL	0.20 (0.30)	0.75 (1.00)	0.20 (0.30)	LOW, 0.0 (0.40)	0.0 (0.10)
SYSTEMS MONITORING		0.75 (0.70)	0.20 (0.00)	0.20 (0.10)	0.0 (0.00)
COMMUNICATION			0.75 (0.90)	0.75 (1.00)	0.50 (0.50)
SURVEILLANCE				0.0 (0.00)	0.20 (0.30)
SEARCH					0.10 (0.30)
NAVIGATION					

Figure 4. Predicted and measured function interlace coefficients.

Figure 4, as the data in brackets.

It can be seen from the comparison of the two sets of numbers that the model did show some predictive value. For the most part, the model results appear to be on the conservative side. It is somewhat difficult to predict, for example, that the workload of flight control with or without a communications task is the same, although that was the simulation result.

These conditions have not been tried out in a full aircraft environment. I would like to know, for example, what happens in an aircraft approach to landing where the situation stress is high and workloads are high. At the moment, it would appear from these preliminary results that an analytically derived estimate of operator workload can be improved by the application of the function interlace hypothesis.

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A METHODOLOGICAL APPROACH TO DISPLAY DESIGN

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Abstract: *This paper summarizes a methodological approach utilized in two studies performed under sponsorship of the Joint Army-Navy Aircraft Instrumentation Research (JANAIR) Program. These studies had the objective of determining vertical-life aircraft display subsystem requirements for manually controlled formation flight and steep-angle approach to landing under Instrument Flight Rule (IFR) flight conditions.*

Because of the complexity of the control task involved, a high degree of pilot display augmentation or quickening was required. The approach taken to define display augmentation requirements involved the use of both control-analysis techniques and man-in-the-loop task simulation in four basic stages of study conduct.

Results of these studies have demonstrated this approach to be an efficient means for establishing display-augmentation requirements for complex manual-control task performance, and have further indicated augmentation characteristics to be a more significant determinant of complex task performance than the format of the display within which this information is integrated. Preparations for flight-test validation of simulation study results are in progress.

INTRODUCTION

The importance of considering the man/machine interface early in the development of new avionic system concepts, and of supporting the objective to provide military vertical-lift aircraft with the capability of low-visibility or IFR operation led the Joint Army-Navy Instrumentation Research (JANAIR) working group to initiate investigations addressing display problems for two particular IFR capabilities: steep angle approach (SAA) and formation flight (FF). These independent investigations (Wolf, 1972; Anderson, 1972) performed by Honeywell, Inc., had the specific objective of establishing display information and associated subsystem requirements for manually-controlled, vertical-lift aircraft flight under IFR conditions. The objective was not to design a specific system but rather to provide baseline data and alternatives for design, and to develop a basis for better definition of steep-angle approach/formation flight problems and system requirements.

The objective of the initial phase of both investigations was to establish display information requirements. However, because realistic display information requirements cannot be established in isolation from the total system, the programs evolved into the broader purpose of defining and validating total display and display-related system concepts from the pilot's viewpoint. The basic problem was viewed as finding acceptable substitutes for visual cues to permit the IFR capability with minimum avionic system sophistication and within current state of the art. Combinations of sensing equipment, computation, and cockpit instrumentation were defined to substitute for visual cues as shown in Figure 1.

The remainder of this paper summarizes the methodological approach utilized and the reasons for this particular approach, and presents sample results demonstrating the utility of the method.

METHODOLOGY

The methodology summarized below actually evolved during the conduct of the two JANAIR programs noted above. Both programs consisted of a series of study phases conducted over a five-year period, with the formation-flight program beginning first.

The objective of the initial formation-flight program was to define pilot information requirements and to demonstrate display formats appropriate for helicopter IFR formation flight. The approach adopted was to perform a standard pilot-information analysis, define alternative display formats containing specified information parameters, and then to evaluate the alternative formats via man-in-the-loop simulation. Results from this first study demonstrated the importance of display augmentation (quickening) for this complex control task and indicated that the control laws required to drive the display-augmentation symbols could have a greater influence

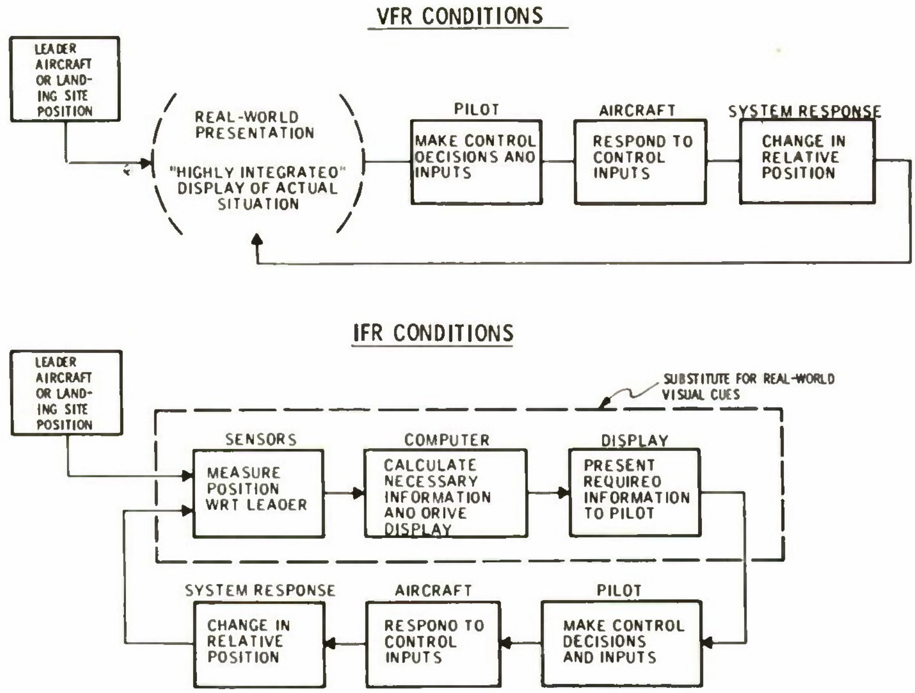

Figure 1. VFR and IFR visual information sources.

on system performance than the specific display format utilized.

This preliminary finding led us to re-examine our methodology. Because the display control laws seemed to influence performance significantly, and because it was very time consuming to fully investigate the variety of control-equation terms and gains through simulation, some type of control analysis was needed to efficiently identify viable display augmentation and control system concepts. In addition, awareness of the importance of system and environmental characteristics on manual control performance led to a requirement to develop a method for systematically introducing these characteristics into the evaluation.

The steep-approach investigation, initiated about one year after the FF study, benefited from what was learned on this initial formation-flight study.

GENERAL OUTLINE OF METHODOLOGY

The elements of the methodology for display design developed during these programs are shown in Figure 2. The sequence in which these elements were performed implies an iterative or "closed-loop" process, indicating that results of a given study frequently influenced the definition of subsequent study objectives, or furnished a basis for modifying system-simulation models used. Significant features of the methodology are discussed in further detail below.

Control analysis. An important first step in the display design process is to find out what is required to control the vehicle under a particular set of conditions. In our programs we viewed the situation as an automatic-control problem as shown for a single control axis in Figure 3. The control system, vehicle dynamics, and situation geometry were linearized and put into transfer function form. In addition, simple pilot models were inserted into the control analysis.

This linearized control system approach is an initial step in understanding pilot performance. It serves as a tool for initial display/control law studies, helping to identify the form of the control law and to provide initial gain values. Preliminary man-in-the-loop simulation is then used to modify the control laws to improve performance under the more realistic conditions of the system simulation.

Select display format candidates. On the basis of both the information and control analysis, viable display-format candidates were selected. In the programs discussed here, both existing and "invented" formats were investigated. The primary emphasis in our work was on the display information content. We were not overly concerned with the coding and symbology aspects of display design.

Develop test plan. System performance analysis by simulation, especially where the human operator is included, can involve many

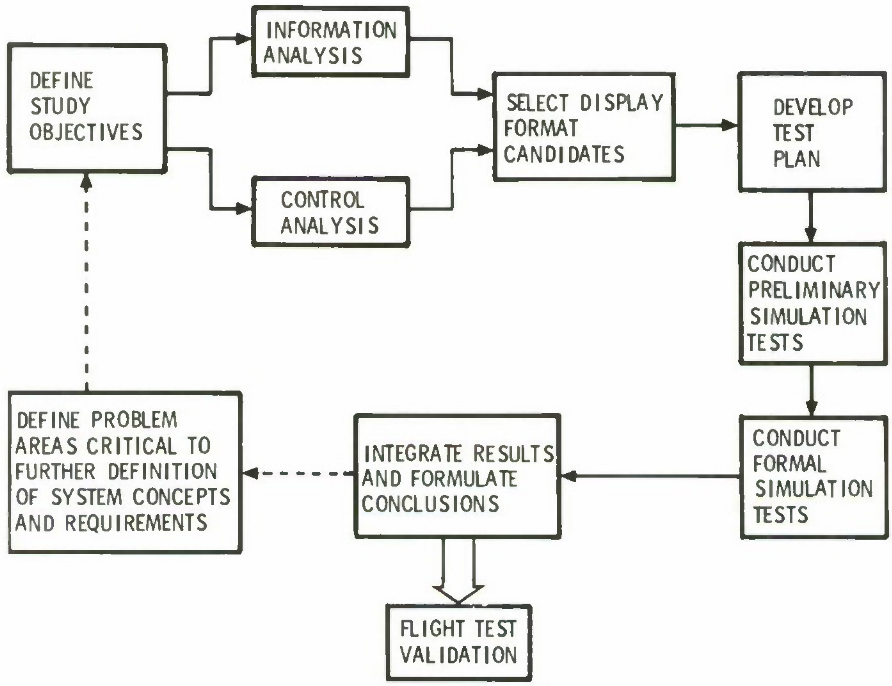

Figure 2. General outline of display design methodology.

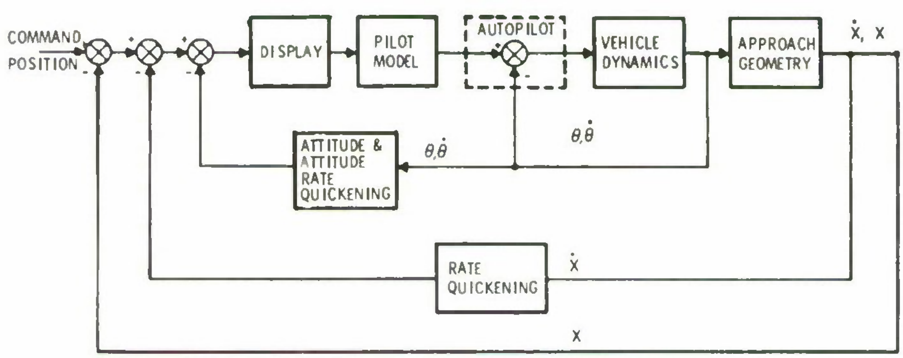

Figure 3. SAA control/display block diagram.

hours of simulator runs. Considerable emphasis was, therefore, placed on the development of systematic test plans to ensure meaningful results. Careful attention to the test plan was also important because of the large number of experimental variables that had to be considered. For example, during the course of the SAA program, 13 experimental variables were investigated. It was obviously not practical to investigate interaction effects among all the variables. In the SAA program, performance data were obtained from a total of 332 treatment combinations of a possible total of over one million combinations required to evaluate interactions of all the variables and associated levels tested. The variables studied and the number of levels utilized for each phase of this particular program are outlined in Table 1.

Conduct simulations. The basic tool used for system evaluation in the programs was man-in-the-loop, fixed base simulation. Each phase of formal simulation is preceded by a preliminary simulation phase to accomplish the following:

- Refinement of procedures.
- Simulator verification of system parameters and variable levels selected for evaluation.
- Familiarization and training of pilot subjects.

Formal simulations were then conducted in accordance with a prescribed test plan to collect performance data on selected treatment combinations. In our studies, sufficient preliminary evaluation was made of all aspects

TABLE 1

SAA VARIABLES INVESTIGATED FOR EACH TASK

VARIABLES EVALUATED	STUDY PHASES					
	TASK I	TASK II	TASK III	TASK IV	TASK V	TASK VI
DISPLAY FORMATS	(4)*	(2)	(2)	(2)		(2)
APPROACH ANGLES	(3)	(2)	(2)	(2)		(2)
AIRCRAFT TYPES	(2)	(2)	(2)			
APPROACH PROFILES	(2)					
SIGNAL FILTER LAGS		(3)	(2)			
SIGNAL NOISE LEVELS		(3)	(2)		(3)	
QUICKENING GAINS		(2)				
CONTROL AUGMENTATION MODES			(4)			
WIND DIRECTIONS				(3)		
WIND VELOCITIES				(3)		
SIGNAL DATA RATES					(5)	
CONTINGENCY EVENTS						(3)
TIME OF EVENT OCCURRENCE						(3)

*FACTORS EVALUATED AS EXPERIMENTAL VARIABLES, AND NUMBER OF LEVELS OF EACH VARIABLE.

of the formal test plan to assure that no change in the plan or treatment levels selected would be required during formal-simulation "production runs."

Iteration process. A central element in this display design methodology is an iterative procedure to evaluate performance. Thus, each study forms a basis for the following study. The iteration permits a more thorough and flexible design procedure by permitting the problems uncovered and experience gained on a particular investigation to influence subsequent study objectives. In these studies, alternate display formats were first evaluated under ideal conditions (perfect sensors, no turbulence effects, etc.) to verify display control law concepts and to reduce the number of display format candidates to be considered further. Then systematically, realistic system and environmental characteristics were introduced to determine performance sensitivities to these effects.

Conduct flight-test verifications. Although not part of the study programs described in Wolf (1972) and Anderson, et al. (1972), flight-testing is shown in Figure 2 as a logical and necessary final step to verify results and recommendations derived from a system simulation. Simulation validity (and cost) tends to be a direct function of how well the simulator duplicates relevant dynamics and pilot cues associated with the real-world system. Conversely, simulation flexibility is usually inversely related to simulation validity. In a research program where several different system concepts must be examined, flexibility becomes a significant feature. Because of its flexibility and relatively low cost, fixed-base simulation was chosen as the primary evaluation tool in the SAA and FF programs.

We hope to confirm the validity of the fixed-based simulation technique during a current U. S. Army ECOM flight test program studying IFR steep approaches with a UH-1 helicopter. This is the same vehicle used to collect a majority of our simulation data. A flight director computer has been modified to duplicate as closely as possible the display augmentation concepts developed during simulation, and will be tested inflight as part of the Army's preparation for the upcoming evaluation of National Microwave Landing System concepts and hardware.

CONCLUSIONS

Results of the two study programs in which the above-outlined methodology has been applied demonstrate this approach to be a workable and efficient means for establishing display-augmentation requirements for complex manual-control task performance. The approach includes simultaneous progressions from simple to more complete problem characterization, and from the analytical/simulation method of problem solution to flight-test verification of solutions obtained. Each work step outlined by this methodology has been found to offer sufficient information and guidance for successful conduct of the subsequent step.

Hindsight indicates, for example, that had the manual-control problems studied been

first addressed by initially simulating a greater number of relevant "real-world" factors than the basic task elements (i.e., displays, vehicles, and mission profiles), considerably more time and effort would have been expended in reaching a comparable scope of final results. In terms of what we hope to be an accurate foresight, the extensive empirical data base generated during task-simulation phases is anticipated to significantly aid flight-test planning and execution (e.g., reduced costs and greater safety). Replication of only a point sampling of all relevant system and environmental variable-level combinations tested in simulation is presently considered to be sufficient for a reasonable inflight validation of the existing simulator-derived performance data base.

The method permits an evaluation of a large number of system and environmental conditions in a systematic way. Further, through the establishment of repeatable baseline data, the method permits a very efficient way of evaluating new flight mode characteristics since several steps in the methodology can be omitted or reduced in the level of effort required. Results from the steep approach and formation flight studies were similar in several respects (e.g., form of the display augmentation equations and the conclusion that task performance is more dependent on augmentation characteristics than on display format). These results, for example, could now be applied to defining augmented display requirements for a terrain-following flight mode, with greatly reduced effort required to establish display subsystem requirements for this mode.

Figures 4 and 5 illustrate summary data samples from the FF study series, and are included in this paper to exemplify results from these studies we believe to be relatively generalizable concerning augmented display design. Figure 4 indicates the extent of performance improvement possible in complex tasks by utilizing display augmentation. Three levels of augmentation are shown for two different formation-flight display format concepts. The PPI (Plan Position Indicator) is an electronic horizontal-situation display format integrated with command information. The Perspective Display is an electronic vertical-situation display containing the same augmentation (command) information, but

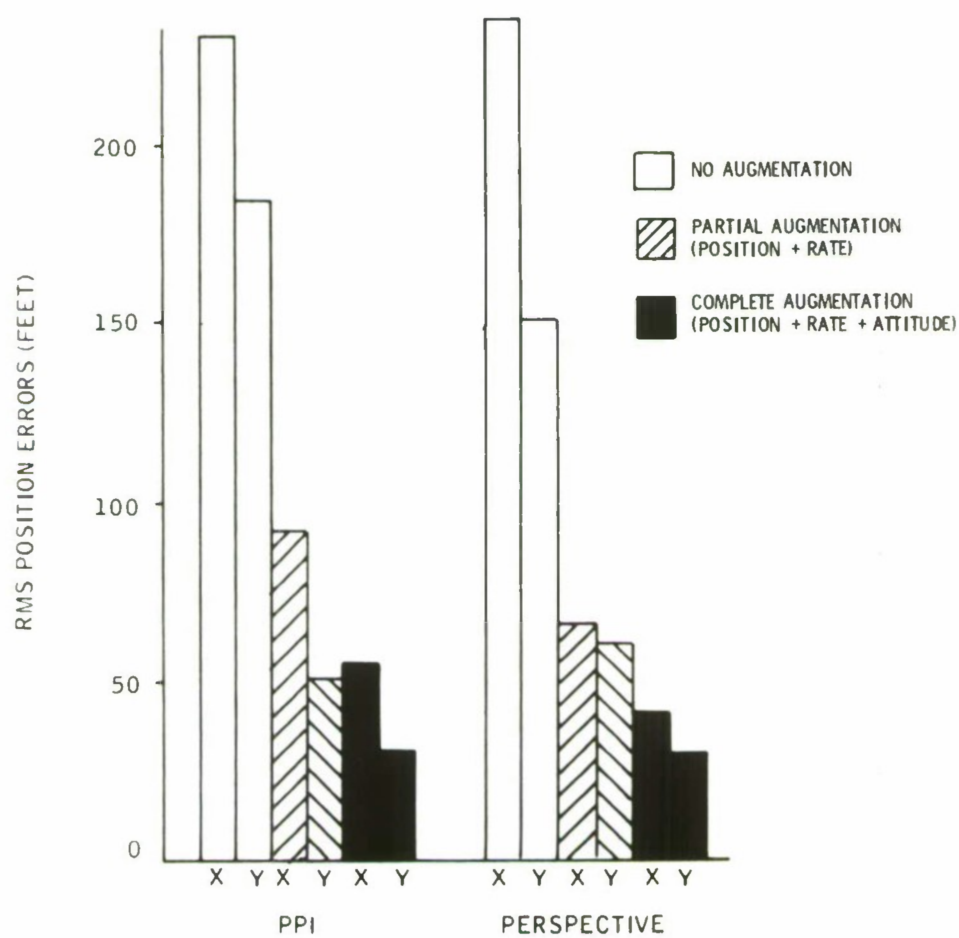

Figure 4. Performance with various levels of display augmentation.

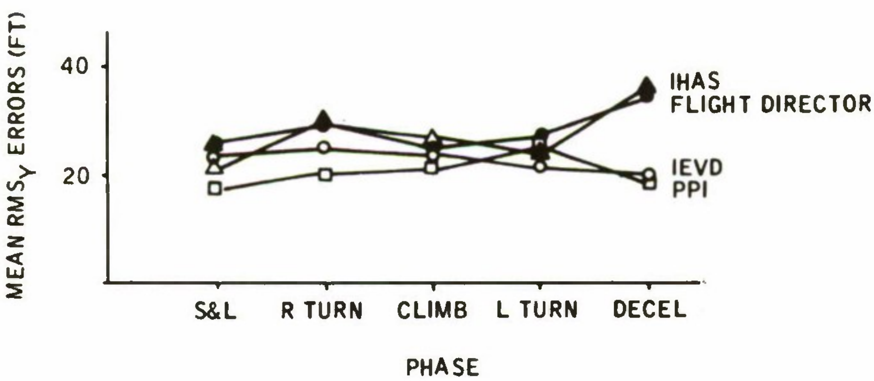

Figure 5. Lateral errors versus flight phases.

utilizing the concept of a symbolic representation of the pilot's VFR view out the window. A comparison of lateral errors in formation flight using four different display formats is shown in Figure 5. In addition to the PPI format data, results are shown for three vertical situation display formats:

- Electromechanical flight director system
- Simulated IHAS (Integrated Helicopter Avionics System) electronic display format
- Simulated IEVD (Integrated Electronic Vertical Display) display format

These data demonstrate that performance is very similar when the same display augmentation concept is utilized.

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